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Evaluation of Alternatives to Sound Barrier Walls

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JOINT TRANSPORTATION RESEARCH PROGRAM

INDIANA DEPARTMENT OF TRANSPORTATION
AND PURDUE UNIVERSITY



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16. Abstract <p>The existing INDOT's noise wall specification was developed primarily on the basis of knowledge of the conventional precast concrete panel systems. Currently, the constructed cost of conventional noise walls is approximately \$2 million per linear mile. The noise wall is considered to be cost effective when a 5 dBA reduction can be achieved at a cost of no more than \$25,000 per benefited receiver or \$30,000 per benefited receiver in those cases where a majority of the receivers were in place prior to construction of the highway. In many areas, however, the above cost-effectiveness criteria are exceeded with the result that the areas are not eligible for federal-aid funding for noise abatement. Consequently, the residents in these areas are dissatisfied that no noise reduction measures are provided to them. Several alternative options may be considered by INDOT to address the above issues. The first option would be to raise the cost per receiver to make more areas eligible for noise walls. The second option would be to do nothing. The third option would be to adopt an optional line of sight (LOS) wall policy to improve customer satisfaction at a less expensive cost.</p> <p>Critical review was conducted on the current traffic noise policies by state DOTs nationwide, including Type II project participation, reasonableness of noise abatement, cost effectiveness of noise abatement, and third party funding. Four different types of noise barriers, including one conventional precast concrete wall and three LOS walls were installed in the study areas for field investigation. Evaluation was made on the issues relating to the construction, cost and structures of the installed noise walls, particularly the LOS walls. Pre- and post-installation noise measurements were made in the field to determine the noise reductions of the installed noise walls. Psychoacoustic-based approach was utilized to further evaluate compare the field acoustic performance of these four noise walls. FHWA TNM 2.5 was also employed to predict the noise level in the design year and address the sensitivity issues associated with traffic volume, vehicle speed, noise wall height, noise wall length, and noise reduction coefficient of noise wall. Furthermore, community noise surveys were conducted before and after the installation of noise walls to identify public perception of the LOS wall performance and public involvement in noise abatement.</p> <p>Main findings and recommendations were made to modify INDOT traffic noise policy and noise wall specifications.</p>			
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EXECUTIVE SUMMARY

EVALUATION OF ALTERNATIVES TO SOUND BARRIER WALLS

Introduction

The present INDOT Traffic Noise Policy was distributed in January of 2007, and applies solely to Type I projects. The existing noise wall specification was developed primarily on the basis of knowledge of the conventional precast concrete panel systems. An acoustic profile for the wall height is determined from a model based on an absorptive surface. Currently, the constructed cost of conventional noise walls is approximately \$2 million per linear mile. The noise wall is considered to be cost-effective when a 5 dBA reduction can be achieved at a cost of no more than \$25,000 per benefited receiver for new development or \$30,000 per benefited receiver in those cases where a majority of the receivers were in place prior to construction of the highway. In many areas, the above cost-effectiveness criteria are exceeded with the result that the areas are not eligible for federal-aid funding for noise abatement. Consequently, the residents in these areas are dissatisfied that no noise reduction measures are provided to them.

There are several alternative options that may be considered to address the above issues. The first option would be to raise the cost per receiver to make more areas eligible for noise walls. This alternative will raise the level of customer satisfaction, but incur greater project costs. The estimated impact of raising the cost per receiver from \$25,000 to \$40,000 is over \$50 million to \$100 million in future construction costs. The second alternative option would be to do nothing. Its main disadvantage is the continued residents' dissatisfaction. The third option would be to adopt an optional line of sight (LOS) wall policy. In this study, the LOS wall refers to a wall that is just tall enough to break the horizontal line of sight between the roadway and homes. While the LOS wall does not fit into the current noise wall policy and could not use federal funds for construction, it may achieve a noise reduction of 5 dBA and provide a mitigating measure to improve customer satisfaction at a less expensive cost than conventional noise walls. In addition, the current INDOT noise policy does not allow for private funds to be used to reduce the cost per receiver. Nevertheless, the LOS wall policy could include the option to require a portion of the cost to be provided from private funds. The LOS wall policy would be optional as funds are available, not a mandate.

Knowledge and information learned about the effectiveness of materials used in the LOS walls could also be used to modify INDOT's noise wall specifications, and reduce the cost of noise walls on future projects. The research results will be used to upgrade the agency's current practice for traffic noise mitigation and make recommendations for policy revisions. The research results can also be used for media outreach to convey the agency's new message to the public in a timely manner.

The objective of the proposed research project is fivefold: (a) to conduct a synthesis of other DOTs' traffic noise policies, such as standards, specifications, and requirements, particularly current practices, cost-effectiveness criteria, public involvement, and alternate measures to conventional noise walls; (b) to evaluate the alternatives to conventional noise walls; (c) to perform traffic noise and abatement analysis of the LOS and conventional noise walls at the interchange of I-465 and Keystone Avenue; (d) to conduct surveys assessing customer perception and satisfaction with LOS walls as compared to conventional noise walls; and (e)

to evaluate the performance of different LOS walls, including construction costs, noise reduction, acoustic properties, structural condition, and durability.

Findings

State DOT Traffic Noise Policies

Fourteen state DOTs opt to participate in Type II projects. In the Midwest, Illinois, Michigan, and Ohio have participated in Type II projects. Wisconsin has established the WisDOT Retrofit Noise Barrier Program that consists of a list of state-funded, stand-alone noise abatement projects on existing highways. INDOT currently does not participate in Type II projects.

Eighteen state DOTs define a substantial noise increase of 10 dBA and twenty-three state DOTs define a substantial noise increase of 15 dBA. In the Midwest, a substantial noise increase of 15 dBA is employed by Indiana and Wisconsin, 10 dBA by Kentucky, Michigan, and Ohio, and 14 dBA by Illinois.

Nineteen state DOTs have established a maximum height between 14 ft. to 30 ft. for noise walls. A maximum height of 20 ft., 25 ft. and 30 ft. is defined by 37%, 26%, and 16% of the state DOTs, respectively. In the Midwest, Ohio defines a maximum noise wall height of 25 ft.; the others do not have a specific maximum wall height limitation.

Forty-nine state DOTs consider a noise abatement to be acoustically feasible if a noise reduction of at least 5 dBA is achieved at the impacted receptors. One state DOT requires a minimum of 9 dBA reduction for at least one impacted receiver. There are two methods for defining the number of impacted receptors used to assess the acoustic feasibility. In the first method, currently used by thirty state DOTs, a minimum noise reduction is required for at least 1 impacted receptor by nine state DOTs, for the majority (50% + 1) of all impacted receptors by seven state DOTs (including INDOT), and for at least 50% of all impacted receptors by five state DOTs.

The second method, currently used by sixteen state DOTs is to define a specific number out of the impacted receptors in the front row. A noise reduction of at least 5 dBA is required at 50% + 1 of the impacted receptors in the front row by four state DOTs, at 75% or more of the impacted receptors in the front row by three state DOTs, and at 50% or more of the impacted receptors in the front row by two state DOTs. Three state DOTs require a noise reduction of at least 5 dBA without specifying the number of impacted receptors.

The cost-effectiveness can be calculated using either the actual construction cost, the cost per square foot, or the maximum square footage per benefited receptor. Forty-three state DOTs (including INDOT) use the allowable cost per benefited receptor, which varies between \$20,000 and \$60,000 with an average of \$35,227 per benefited receptor. Eleven state DOTs define an allowable cost of \$20,000–\$25,000 per benefited receptor and thirty-two state DOTs define an allowable cost of more than \$25,000 per benefited receptor. The allowable costs for other Midwest state DOTs vary between \$30,000 and \$42,500 with an average of \$34,600 per benefited receptor. The current allowable cost is \$25,000 per benefited receptor for INDOT and is the same allowable cost in 2007. Seven state DOTs utilize the maximum square footage per benefited receptor to measure the cost-effectiveness. The maximum square footage varies between 1000 ft² and 2700 ft² per benefited receptor. No state DOTs in the Midwest use the maximum square footage per benefited receptor currently.

The new FHWA noise regulation mandates a noise reduction design goal between 7 dBA and 10 dBA at benefited receptors.

Thirty-six state DOTs define a noise reduction design goal of 7 dBA and seven state DOTs define a noise reduction design goal of 10 dBA. In the Midwest, Indiana, Kentucky, Michigan and Ohio define 7 dBA as the noise reduction design goal. The noise reduction design goal is 8 dBA for Illinois and 9 dBA for Wisconsin.

FHWA does not allow use of third party funding to reduce the cost of the noise barrier for Type I Federal-aid projects. Third party funding can only be used to pay for additional features, including landscaping, aesthetic treatments, functional enhancements (sound-absorbing treatment), and access doors. Several state DOTs allow the use of third party funding in some special situations. Third party funding is mainly used to construct noise abatement measures within the State right-of-way. Third party funding is mainly used to construct noise abatement measures for either Type II projects or retrofit projects. In cases where is not eligible for federal-aid funding for noise abatement, and other groups, including local government and residents, insist on providing a noise abatement measure, other groups must assume 100% of all costs, including pre-engineering cost, construction cost, and maintenance cost under an agreement signed by the state DOT and the local municipality acting for other groups.

Construction, Cost, and Structural Evaluation

Metal walls are vulnerable to the impacts of rocks and errant vehicles and require protection guardrails. Wood walls are prone to weathering, resulting in gaps, and therefore reduced acoustic performance. The fiberglass noise walls may cost as much as the precast concrete wall. The acrylic noise walls may cost two times as much as the precast concrete wall to achieve the same noise reduction. The vegetation noise walls may not be UV-stable and the maintenance, particularly watering to keep the plants alive, is costly.

The construction cost of the precast concrete noise wall was close to that of the CMU block noise wall. The amount of work of the noise wall may affect the unit construction cost significantly. The larger the amount of work, the lower the unit construction cost. The unit construction cost of precast concrete noise walls falls within a range of \$32.6/ft² to \$35.1/ft² at a confidence level of 95% in the past. The regional cost differences of the construction of noise walls are not evident within the State. While the construction costs of noise walls have experienced fluctuations over the past two decades, overall it demonstrates an increasing tendency with time.

The construction cost of noise walls is commonly broken down to three pay items by INDOT, including barrier design and layout, barrier panels, and panel erection. For the conventional Durisol precast concrete noise wall, the three pay items accounted for 2.8%, 75.8%, and 21.4% of the total cost, respectively. For the LOS walls, the three pay items shared on average 10.1%, 62.9%, and 27.0% of the total construction cost, respectively. The unit cost for LOS walls (\$30/ft²) was more than that for the Durisol precast concrete wall (\$23.4/ft²). This is because the competitive bids for the LOS walls were not available due to the small amount of work and because the foundation for the Durisol precast concrete wall was utilized for the LOS walls.

All of these four noise walls demonstrated satisfactory surface conditions in terms of integrity and color right after construction. No chipping, spalling, cracking, or color fading was observed. However, waviness was observed in the outer skin on one portion of the Noise D-Fence wall. Ground penetration radar (GPR) testing was conducted right after construction to evaluate the initial structural integrity of these noise walls. It was found that at this time, each panel has consistent dielectric properties in the horizontal and thickness directions, respectively.

Pre- and Post-installation Noise Levels

The hourly noise variation followed a trend similar to the hourly traffic variation. The maximum hourly noise variation was 2 dBA. The greatest noise level occurred approximately at 8 a.m. The noise levels on weekends were much less than those on weekdays. The maximum weekly noise difference was 1.2 dBA over the weekdays. There should be no noticeable differences in the noise measurements regardless of the time of day and day of week (weekdays) in the study areas.

In NSA1 (LOS walls, Temple Ave.), the pre-installation noise levels at all 23 homes varied from 55.5 dBA to 71.7 dBA with an average of 65.0 dBA. The post-installation noise levels dropped to 50.6–67.0 dBA with an average of 60.2 dBA. The noise reduction varied between 2.5 dBA and 12.2 dBA with an average of 4.8 dBA. Also, 63.6% of the impacted homes received a noise reduction ≥ 5 dBA, which indicates that the LOS walls are acoustically feasible.

In NSA2 (conventional Durisol noise wall, Retreat Apt), the pre-installation noise levels ranged between 63.2 dBA and 73.2 dBA with an average of 68.2 dBA. The post-installation noise levels varied between 57.8 dBA and 65.6 dBA with an average of 62.0 dBA. The noise reduction varied from 3.3 dBA to 7.9 dBA with an average of 6.1 dBA. For the impacted homes, 75.0% received a noise reduction ≥ 5 dBA. This confirms that the conventional Durisol noise walls are acoustically feasible in NSA2.

In NSA3 (conventional Durisol noise walls, East 101 St.), the pre-installation noise levels ranged between 60.5 dBA and 69.9 dBA with an average of 65.5 dBA. The post-installation noise levels varied between 58.0 dBA and 64.0 dBA with an average of 61.6 dBA. The noise reduction varied from 3.3 dBA to 7.9 dBA with an average of 6.1 dBA. All post-installation noise measurements were below the NAC, i.e., 66 dBA.

The pre-installation noise level decreased as the distance or elevation difference increased. The pre-installation noise level was more closely related to the elevation than the distance. After installing the noise walls, the principles of sound propagation remain valid. However, the strongest correlation arose between the post-installation noise level and distance. Also, the post-installation noise level was more closely associated with the noise wall height than the elevation difference. This may imply the effect of noise walls, particularly sound diffraction. The noise reduction does not necessarily always decrease as the distance increases.

Psychoacoustic-based Noise Wall Effectiveness Evaluation

Psychoacoustic-based noise wall effectiveness evaluation was made through the insertion loss spectrum density and normalized annoyance. It was shown that the conventional Durisol noise wall is more effective in noise reduction. The height of the Durisol noise wall could affect its noise reduction capability. The shorter the Durisol noise wall, the less effective the noise reduction, especially in higher frequency bands. The LOS walls are less effective than the Durisol noise wall. However, LOS walls can reduce some noise impact. Among AAC, Noise D-Fence, and Sanders Precast walls, AAC wall is less effective than Noise D-Fence and Sanders Precast walls. Based on the psychoacoustic annoyance as a measure, Sanders Precast walls can perform slightly better than Noise D-Fence walls in noise reduction.

Prediction and Analysis of Traffic Noise over Design Year

The performances of the constructed prediction models varied from area to area, from model to model, and from pre-installation to post-installation. The 95% confidence interval for the pre-installation model in NSA2 falls completely outside the valid

range of ± 3 dBA. The 95% confidence intervals for other models fall within the valid range of ± 3 dBA. In NSA2, the distribution of noise discrepancies is strongly, positively skewed for the constructed pre-installation model. Also, the pre-installation noise discrepancies in NSA2 exhibit very poor correlation with distance and elevation. Therefore, this model might involve some consistent errors and can be adjusted simply by adding 5 dBA to the predicted value.

The pre-installation noise levels predicted with DGAC, OGAC, and Average pavements are respectively 2.9 dBA, 3.5 dBA and 2.0 dBA less than that with PCC. However, the noise differences due to the pavement type become less after installing the noise walls.

The noise level increases by around 5 dBA as traffic speed increases from 50 mph to 75 mph, approximately 1 dBA per 5 mph increase in traffic speed. The predicted noise levels are all below 66 dBA at 55 mph. It was found that the effect of traffic speed on the noise level is independent of the ground condition to some extent and is probably dependent on the noise prediction methodologies utilized by TNM 2.5. The effect of traffic volume on the noise level is also independent of the ground condition, which is solely due to the noise prediction methodologies used by TNM 2.5. The noise level increases by approximately 1.7 dBA from the first year to the design year regardless of the area. In other words, the traffic noise level increases by less than 0.1 dBA each year.

The predicted noise level decreases as NRC increases. However, the amount of noise reduction is completely negligible. The total amount of noise reduction is 0.2 dBA when the NRC increases from 0 to 0.95. This indicates that the Durisol, AAC, Noise D-Fence, and Sanders noise walls may provide similar acoustic performance to the protected side.

As the noise wall height increases from 10 ft. to 24 ft., the noise level decreases by about 5.6 dBA regardless of the study area. However, the decrease rate drops as the noise wall height increases, particularly when the noise wall exceeds 16 feet high. The effectiveness of noise reduction by increasing the noise wall height also varies with the receptor's distance and elevation. The noise reduction decreases as the distance increases or the elevation decreases.

When the Sanders precast wall is extended 30 ft. east, the noise reduction is 0.2 dBA, 0.3 dBA, and 0.3 dBA at R1, R2, and R3, respectively. A noise reduction of 0.5 dBA can also be achieved at R27 by extending the AAC wall 30 ft. west. In other words, making the Sanders or AAC noise walls longer may not provide noise reduction as much as expected at those houses living close to the ends of LOS walls.

After installing the noise walls, most of the receivers in the three areas are well outside the N66 noise contours. The predicted average noise reductions are 4.4 dBA, 11.4 dBA, and 8.7 dBA right after installing the noise walls in NSA1, NSA2, and NSA3, respectively. In the end of the design year, only 33% of the receivers in NSA1, 56% of the receivers in NSA2, and 100% of the receivers in NSA3 can achieve a noise reduction of 5 dBA or more.

Pre- and Post-installation Community Noise Surveys

Both the pre- and post-installation surveys consisted mainly of the same respondents. The response rate for the owner-occupied homes was approximately 12% greater than that for the renter-occupied homes. Almost 90% of the respondents considered traffic noise their greatest concern. About 62% of the respondents perceived a significant increase in both traffic volume and truck traffic volume during the time they had lived in their homes. The longer the respondents had lived in the study areas, the greater the traffic increase the respondents perceived. However, 87% of the respondents, particularly those could not view the traffic above the noise walls, perceived no change or a decrease in truck traffic before

and after construction. The installation of noise walls produced positive perceptions about the change of truck traffic. Blocking the view of traffic provides some psychological relief to the residents.

Over 84% of the respondents had perceived a significant or moderate increase in traffic noise. The increase of traffic noise occurred gradually and slowly over time. In the pre-installation survey, 70% of the respondents rated the noise level very loud, 27% rated the noise level loud, and 2.7% rated the noise level no problem. About 39% of the respondents perceived noticeable noise on weekdays, and 10% perceived noticeable noise on weekends. No respondents perceived noticeable noise on holidays. The traffic noise level was more noticeable during the daytime, particularly during the after-school time. Also, the noise impact was greater during nighttime than during daytime before installing the noise walls.

In the post-installation survey, 26% of the respondents rated the noise level very loud, 52% rated the noise level loud, and 21% rated the noise level no problem. Obviously, the respondents in the project area received a perceivable noise reduction after the installation of the noise walls. The noise walls significantly mitigated the impacts of traffic noise from I-465 on the respondents' life quality. The greater noise reduction was perceived by the respondents in NSA2 and NSA3 with conventional noise walls than those in NSA1 with LOS walls. The view of traffic above the noise walls might play an important part in respondents' perception of the post-installation noise level and impact. No effects of the respondents' age and gender were identified. The installation of noise walls have improved both safety and security for kids playing in their backyards.

In NSA2 and NSA3 with the conventional noise walls, about 53% of the respondents were pleased with appearance of the conventional noise wall. In NSA1 with the LOS walls, however, about half of the respondents were displeased with appearance of the LOS walls. For these respondents displeased with the appearance of the LOS walls, about 70% responded that the LOS walls should be either higher or longer. About 75% of the respondents felt unhappy about viewing traffic above the noise walls. The waviness occurred in the outer skin on the Noise D-Fence wall might also play an important part in the respondents' perceptions of the appearance of the LOS walls.

Over 70% of the respondents had never complained to the agency about the traffic noise in their neighborhoods. Almost 80% of the respondents were not familiar or had limited familiarity with the federal noise regulations and INDOT noise policy. Also, about 71% of the respondents had limited familiarity or were not familiar with traffic noise abatement measures.

About 66% of the respondents indicated that noise walls should be built even if the cost-effective threshold is exceeded. About 18% of the respondents would accept a cheap alternative to provide some noise reduction. Also, 82% of the respondents expressed no willingness to contribute money if the cost-effective threshold is exceeded. Of those respondents willing to contribute money, the average amount of money they would like to pay is \$2,160.

About 54% of the respondents indicated that alternative walls with limited noise reduction should be built even if the cost-effective threshold is exceeded. When asked if it is worth the money to build these noise walls, about 67% of the respondents in NSA2 or NSA3 with conventional noise walls answered yes and 50% of the respondents answered no in NSA1 with LOS walls.

When asked how the respondents would prefer to receive information on public involvement in traffic noise, about 56% of the respondents would prefer to receive the information by mail, 22% by email, 13% by TV, and 9% by newspaper. No respondent would prefer to receive the information by any type of social media, such as Facebook and Twitter, regardless of respondent's age and gender.

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1. INTRODUCTION

1.1 Problem Statement

Traffic noise abatement is one of the INDOT's strategic commitments to environmental mitigation and our neighborhoods. The present Indiana Department of Transportation (INDOT) Traffic Noise Policy used in this study was distributed in January of 2007 (1), and applies solely to Type I projects. The main goals of this policy are to implement the 23 CFR 772 (2) and the National Environmental Policy Act of 1969 (3), and to provide guidance for the analysis of traffic noise and abatement measures, particularly sound (or noise) walls. The existing noise wall specification was developed primarily on the basis of knowledge of the conventional precast concrete panel systems. An acoustic profile for the wall height is determined from a model based on an absorptive surface. Currently, the constructed cost of conventional noise walls is approximately \$2 million per linear mile. The INDOT criteria for when a noise wall will be constructed were established in light of an allowable cost. The noise wall is considered to be cost effective when a 5 dBA reduction can be achieved at a cost of no more than \$25,000 per benefited receiver or \$30,000 per benefited receiver in those cases where a majority of the receivers were in place prior to construction of the highway. In many areas, however, the above cost-effectiveness criteria are exceeded with the result that the areas are not eligible for federal-aid funding for noise abatement. Consequently, the residents in these areas are dissatisfied that no noise reduction measures are provided to them.

There are several alternative options that may be considered by INDOT to address the above issues. The first option would be to raise the cost per receiver to make more areas eligible for noise walls. This alternative will raise the level of customer satisfaction, but incur greater project costs. The impact of raising the cost per receiver from \$25,000 to \$40,000 estimated by INDOT Construction Management will be over \$50 million to \$100 million in future construction costs. The second alternative option would be to do nothing. The disadvantage of this option is the continued dissatisfaction from residents adjacent to highway projects. The third option would be to adopt an optional line of sight (LOS) wall policy. In this study, the LOS wall refers to as a wall that is just tall enough to break the horizontal line of sight between the highway (noise source) and the home (noise receiver). Since the eye level height at a standing position is 67 in. for the average U.S. adults (4), the height of LOS wall may be around 6 ft. While the LOS wall does not fit into the current noise wall policy and could not use federal funds for construction, it may achieve a 5 dBA noise level reduction (5). Consequently, an LOS wall could provide a measure to improve customer satisfaction at a less expensive cost than conventional noise walls. The current INDOT noise wall policy does not allow for private funds to be used to reduce the cost per receiver. Nevertheless, the

LOS wall policy could include the option to require a portion of the cost to be provided from private funds. The LOS wall policy would be optional as funds are available, not a mandate. Knowledge and information learned about the effectiveness of materials used in the LOS walls could also be used to modify the INDOT's noise wall specifications and reduce the cost of noise walls on future projects.

The knowledge and experience learned from this project will include the state-of-practice noise abatement measures and noise wall alternatives nationwide, costs and noise abatement performance of LOS walls, and customer satisfaction with the LOS walls. The information obtained from this project will also be used for media outreach to timely convey the agency's new message to the public. The research results will be used to upgrade the agency's current practice for traffic noise mitigation and make recommendations for policy revisions. In addition, some States started using the maximum square footage of abatement per receiver instead of the cost per receiver as the cost-effectiveness criteria. This is a significant policy decision that could have major financial impacts on the future construction program. It is apparent that there is an urgent need for research to support a policy decision of how to deal with these issues and identify cost-effective traffic noise reduction countermeasures.

1.2 Research Objectives

The objective of the proposed research project is fivefold: (a) to conduct a synthesis of other DOTs' traffic noise policies, including standards, specifications, and requirements, particularly current practices, cost-effectiveness measurements and criteria, public involvement, and alternate measures to conventional noise walls; (b) to evaluate the alternatives to conventional noise walls; (c) to perform traffic noise and abatement analysis of the LOS and conventional noise walls to be constructed at the interchange of I-465 and Keystone Avenue; (d) to conduct surveys assessing customer perception and satisfaction with LOS walls as compared to conventional noise walls, and (e) to evaluate the performance of LOS walls, including construction costs, noise reduction, acoustic properties, structural condition, and durability. Recommendations will be made for INDOT Traffic Noise Policy revisions.

1.3 Main Tasks and Research Approaches

1.3.1 Cost-Effectiveness Criteria for Considering Noise Walls

The 23 CFR 772 requires each State department of transportation to incorporate the cost-effectiveness criteria for considering noise abatement such as noise walls in their highway traffic noise policy. The cost-effectiveness criteria are established by determining a baseline cost reasonableness value. The baseline cost reasonableness value for noise walls can be the

allowable cost such as the construction cost of noise walls or the cost per receptor. It can also be the maximum square footage per receptor. Most State departments of transportation establish the allowable cost in light of the cost per receptor. The cost per receptor is a cost-effectiveness metric that depends directly on the construction cost and can be easily understood. However, this cost-effectiveness metric may vary significantly due to the fluctuation of construction costs. In past years, as an example, many State DOTs have experienced unprecedented construction cost increase due to the escalation of global fuel price (6). Also, regional cost differences may arise within the State. In light of these considerations, it is necessary to evaluate if the allowable cost in the current INDOT Traffic Noise Policy should be adjusted.

In order to eliminate the possible effect of the construction cost variations, some State Departments of Transportation started using the maximum square footage per receiver, instead of the cost per receiver, as the cost-effectiveness criteria for evaluating the proposed noise wall. The maximum square footage per receiver is a cost-effectiveness criterion that depends on both the area of noise walls required for a 5 dBA noise reduction and the state's noise reduction design goal, i.e., 7 dBA. It does not deteriorate due to the potential escalation in construction costs or inflation over time. It either does not change due to the regional cost differences within the State. This research project will examine the equivalent values of the maximum square footage per receiver for noise walls built over the past years and evaluate the possible use of this metric.

1.3.2 Policy for Considering LOS Walls

In general, LOS walls are smaller and therefore cheaper than conventional noise walls. While LOS walls are typically designed to block the line of sight between a residential (or commercial) area and a structure, LOS walls may also be constructed to reduce noise levels. Since LOS walls are smaller and may have no surface treatment with absorptive materials, they may not provide noise reduction of at least 5 dBA that can commonly be achieved by conventional noise walls. There are some unique advantages with the construction of LOS walls. First, LOS walls provide an alternative to meet the expectation of our communities to some degree at a much less expensive cost. More areas may be justified for noise abatement measures. Second, LOS walls provide a channel to utilize private funds for those projects that do not meet the classification of a Type I projects or those locations where the cost-effectiveness criteria cannot be met. Third, unlike the noise wall policy, the LOS wall policy is not mandated and not necessarily to provide a noise reduction of 5 dBA or more. It becomes more flexible in the design of wall appearance and selection of wall materials, and easier to preserve aesthetic views and scenic vistas to a reasonable extent. For LOS walls that have applied absorptive materials, this research will

evaluate their performance (noise-reduction and durability) and costs.

1.3.3 Acoustic Performance of LOS Walls

Similar to the conventional noise walls, an LOS wall intercepts noise waves and reduces the noise level by transmitting, absorbing, and reflecting the noise. Due to its limited height, the key noise abatement factor of an LOS wall is the mass of the wall that affects its ability to reduce direct noise transmission. The second key factor is the noise absorption of the wall, which is the incident noise that strikes the wall and is not reflected back. Another noise abatement factor is the noise reflection that may be overlooked. When noise strikes the hard surface of an LOS wall, the major part of the noise energy is reflected back. When the reflected noise waves have exactly opposite phase of some other waves, some noise energy would be canceled (7), and so noise is reduced. Therefore, it is of significance to evaluate the acoustic performance of the LOS wall at different noise frequencies.

A simple, robust approach to evaluate the noise abatement performance of an LOS wall is to determine insertion loss in each frequency at each location over the time. Noise data acquisition will be performed at different time and different locations. In-house designed algorithms will be developed to filter and analyze the signals. Once the insertion loss spectrum has been determined, it can also be utilized to improve the design of both conventional noise walls and LOS walls. This study will evaluate the acoustic performance of LOS walls and identify potential changes with noise reduction effectiveness over time.

1.3.4 Material Properties of LOS Walls

The acoustic performance of an LOS wall relies not only on the shape of wall and the roughness of wall surface, but also the properties of the wall building materials. Due to the effect of sun-light, water, temperature, and pollution, an LOS wall may experience aging, corrosion, staining, efflorescence and other damages. Therefore, its material properties deteriorate over time so that its acoustic properties could also deteriorate dramatically. In addition, the effect of freeze-thaw cycles may produce a substantial loss of wall material mass, volume instability, and surface defects. This will further affect the durability of an LOS wall, and result in structural inadequacies. It is needed to evaluate the durability of LOS walls in light of material properties and structural conditions.

In the proposed research projects, the ground penetrating radar (GPR) will be employed to evaluate the change of material properties and structural conditions of the LOS walls. GPR is a high-frequency electromagnetic method and has been used for non-destructive evaluation (NDT) of pavement, retaining walls, and masonry structures. However, no study has been published for using GPR to evaluate noise walls.

GPR testing is based on the use of impact-generated high-frequency compressional P-waves that travel through the structure and are reflected by internal flaws and external surfaces. Therefore, the information produced by GPR may be used to assess the structural conditions of LOS walls. In addition to the use of GPR, visual inspection will be conducted to identify the defects of wall surfaces.

1.3.5 Work Plan

The proposed project will cover traffic noise prediction, analysis of traffic noise impacts, and analysis of noise abatement for both the conventional noise and LOS walls that will be built at the interchange of I-465 and Keystone Avenue. The main tasks are defined as follows:

- **Synthesis of State DOTs' traffic noise policies.** This includes a critical review of traffic noise standards, noise abatement requirements, and procedures for considering noise abatement measures for different types of projects. Focus will be on the cost-effectiveness criteria for considering noise walls, state-of-practice alternatives to noise walls, third party funds, and public involvement in noise abatement decision making.
- **Traffic data collection and analysis.** This task will cover collection and analysis of traffic data acquired using video cameras and Automatic Traffic Recorder (ATR) sites. The video image traffic data will be collected while measuring noise levels and processed using the automatic image processing system developed in a previous JTRP study (8). The ATC data will be analyzed using an appropriate tool. The analysis results, such as traffic volumes, traffic compositions, and traffic speeds, are critical inputs for traffic noise prediction, noise impact analysis, and noise abatement analysis in the design year. The information is also useful for determining the loudest hours for measuring noise levels.
- **Determination of noise levels.** Noise levels will be measured at each receiver or representative set of receivers before and after construction of both the conventional noise walls as well as the LOS walls. The measurements will be taken in accordance with FHWA guidance (9) and ANSI S12.8 (10) at a time of day that reflects the loudest hourly noise level occurring on a regular basis under normal traffic conditions. Noise level measurements will also be made at different times of the day and at special times, such as weekday and weekend. All noise level measurements will be taken in light of hourly Leq (dBA) using ANSI Type I integrating noise meters.
- **Traffic noise prediction.** The future traffic noise prediction in the design year will be performed for all alternatives, including do-nothing, conventional noise walls, and LOS walls, using the software, Federal Highway Administration Traffic Noise Model (TNM Version 2.5) (11), which is specified in the 23 CFR 772. The future traffic noise prediction will simulate the average pavement type, traffic characteristics that would yield the worst noise impact, actual roadway configuration, including number of lanes, and vertical and horizontal alignments, and actual ground conditions.
- **Insertion loss spectrum analysis.** The insertion loss spectrum analysis for both the conventional noise walls

as well as the LOS walls will be evaluated based on in-situ noise measurements. Similar to the reverberation room method in FHWA-PD-96-046, the proposed method measure and compute the insertion loss after the installation of a noise barrier. This will be done by placing microphones (receivers) at different receiver locations to measure to the noise pressure level as FHWA-PD-96-046. In-house designed algorithms and software will be developed to filter and analyze the signals. The insertion loss spectrum analysis not only measures how much overall insertion loss is, but also implies that how effective the wall is in different spectrum. This information is very useful to evaluate new materials and noise abatement walls.

- **Evaluation of noise reduction performance based on human hearing perception.** Psychoacoustic-based noise annoyance reduction capability analysis will be developed to evaluate the effectiveness of noise abatement walls. Psychoacoustic annoyance can quantitatively describe annoyance rating obtained in psychoacoustic experiments. It is well-established and experimentally approved effective method in field to evaluate noise impact to human hearing perception. The psychoacoustic annoyance will be calculated based on the loudness, roughness, sharpness, loudness, and fluctuation. To normalize traffic variations, we will develop a normalized noise annoyance analysis method. This analysis would provide comprehensive and quantitative measure of the noise reduction capability of noise abatement walls at different locations in terms of human hearing perception. This information is very useful to evaluate the effectiveness of abatement walls.
- **Construction cost analysis.** The construction cost analysis will be first performed on the conventional noise walls and the LOS walls under this study. Next, the construction cost analysis will be performed on the noise walls that have been constructed over the past years. This information will be used to determine the increase in construction costs, to identify potential cost differences between the conventional noise walls and the LOS walls, and to adjust the current cost-effectiveness criteria, i.e., the allowable cost for considering noise walls. In addition, the construction costs may be converted into equivalent maximum square footage per receiver so as to assess the feasibility to adopt the maximum footage per receiver as the cost-effectiveness criterion for noise walls.
- **Evaluation of wall structural conditions.** This task is to evaluate the durability of both the conventional noise walls as well as the LOS walls for five years. The evaluation will be undertaken using GPR equipment and visual inspection. The GPR data will be utilized to identify possible defects, mass loss, and volume instability inside the panels of the walls under study. The visual inspection will focus on the surface defects, such as holes, chips and spalls, and color changes.
- **Customer satisfaction survey.** Surveys were performed before and after construction in accordance with the INDOT Traffic Noise Policy. The surveys included questions, such as the current noise levels, residents' attitudes to noise barrier and LOS walls, their perceptions of the costs and effectiveness of both the conventional noise walls and the LOS walls, satisfaction levels after construction of the conventional noise walls and the LOS walls, and third party funding for LOS walls. The survey designs were first submitted to the SAC members for review and approval. The survey options and time

were also determined in consultation with the SAC members.

- **Final report.** A technical report will be submitted to JTRP, business owners, and potential implementers. This report will document the research procedures, data, results and findings, and compile recommendations for INDOT traffic noise policy revisions.

It is intended that this project will provide deliverables as follows:

- Comparison of noise wall policies used by DOTs nationwide, including alternatives to noise walls.
- Recommendations for policy revisions, such as possible increase of the allowable construction cost or adoption of the maximum square footage per receiver as the cost-effectiveness criterion for considering noise walls. Updated construction costs for the conventional noise walls.
- First-hand information on LOS walls, including costs, noise reduction effectiveness, noise reduction performance of the LOS wall materials, and durability for developing LOS wall policy.
- Technical report documenting research procedures, results, and findings.

2. TRAFFIC NOISE POLICIES IMPLEMENTED BY STATE DEPARTMENTS OF TRANSPORTATION

2.1 Federal Highway Traffic Noise Standards

2.1.1 Title 23 CFR Part 772

The National Environmental Policy Act (NEPA) of 1969 (12) provides broad authority and responsibility for addressing adverse effect of highway traffic noise. Federal-Aid Highway Act of 1970 (13) specifically involves abatement of highway traffic noise. In response to this act, FHWA developed a noise standard for new Federal-aid highway projects, i.e., Title 23 CFR Part 772 and promulgated noise regulations which applied to the federal-aid projects. Title 23 CFR Part 772 serves the public need. Its ultimate goal is to provide procedures for noise studies and noise abatement measures to help protect the public's health, welfare and livability, to supply noise abatement criteria, and to establish requirements for information to be given to local officials for use in the planning and design of highways approved pursuant to the Federal-aid Highway Act of 1970. It is mandated that by Title 23 CFR Part 772, state DOTs have to adopt a written Highway Traffic Noise Policy in compliance with FHWA for federal-aid projects and must comply with Title 23 CFR 772 for granting federal-aid highway funds.

Since its first approval, Title 23 CFR 772 has been revised several times. The latest FHWA noise regulations were published July 13, 2010 and became effective on July 13, 2011. The new Title 23 CFR Part 772 consists of ten essential sections, including purpose, noise standards, definitions, applicability, traffic noise prediction, traffic noise impact, noise abatement, federal participation, information for local officials, and con-

struction noise. Each section presents the fundamental procedures, criteria and requirements for analyzing and abating traffic noise, and establishes the guidelines for state DOTs to develop and implement their traffic noise policies. The new Title 23 CFR Part 772 mandates that state DOTs to update their current traffic noise policies in accordance with the new FHWA noise regulations and the updated state traffic noise policies had to be approved by FHWA by July 13, 2011.

2.1.2 Changes to New Title 23 CFR Part 772

Compared with its old edition, the new Title 23 CFR Part 772 has made a number of changes (14), such as reorganization of sections, revision of the Noise Abatement Criteria (NAC), expansion of definitions, and substantive incorporation of the updated FHWA guidance. Summarized in Table 2.1 are those major changes in the new FHWA noise regulation. In Sec. 772.5 Definition, the new Title 23 CFR Part 772, the changes include addition of new variables. First, the variables, such as feasibility, noise reduction design goal, reasonableness and substantial noise increase, are clearly defined in the new noise regulation. This provides necessary clarifications for state DOTs to precisely comply with the federal noise regulation. Second, the projects are divided into Type I, Type II, and Type III projects in the new noise regulation, rather than Type I and Type II projects. The scope of Type I project is expanded to include auxiliary lane, interchange, restriping, weigh station, rest stop, ride-share lot and toll plaza. All projects other than Type I and Type II projects are defined as Type III projects in the new noise regulation.

In Section 772.7 Applicability, the new Title 23 CFR Part 772, state DOTs are invited to participate in Type II projects. If a state DOT opts to participate in Type II projects, the agency has to develop and implement a Type II program for approval by FHWA. In Section 772.11 Analysis of traffic noise impact of the new noise regulation, a substantial noise increase is clearly defined for considering noise analysis and abatement. The analysis procedures are also defined for a Type II project. In Section 772.9 Traffic noise prediction of the new traffic noise regulation, the FHWA Traffic Noise Model (TNM Version 2.5) is designated as the standard noise prediction methodology. For future noise level prediction, the average pavement type is required in analysis. Also, the traffic characteristics producing the worst traffic noise impact in the design year is required in predicting noise levels and assessing noise.

In Sec. 772.13 Analysis of noise abatement of the new noise regulation, the feasibility for considering noise abatement measures is defined to achieve at least a 5 dBA noise reduction at impacted receptors. To assess the reasonableness of the noise abatement measures, a new maximum square footage of abatement per benefited receptor is added to measure the cost-effectiveness of the noise abatement. The state DOTs can still opt to use the cost per benefited receptor to measure the cost-effectiveness. However, it seems

TABLE 2.1
Summaries of Major Changes of New Title 23 CFR Part 772

Section	Changes
Sec. 772.5 Definitions	Feasibility Noise reduction design goal Reasonableness Substantial noise increase Type I project Type II project Type III project
Sec. 772.7 Applicability	Participation in a Type II program
Sec. 772.9 Traffic noise prediction (Sec. 772.17 in old regulation)	Traffic noise model Pavement type
Sec. 772.11 Analysis of traffic noise impact (Sec. 992.9 in old regulation)	Substantial noise increase Type II project
Sec. 772.13 Analysis of noise abatement (Sec. 992.11 in old regulation)	Feasibility Cost-effectiveness Noise reduction goal
Sec. 772.15 Federal participation (Sec. 772.13 in old regulation)	Activity category NAC

that the use of the maximum square footage of abatement per benefited receptor can reduce the effect of inflation. In addition, a noise reduction design goal of 7 dBA to 10 dBA is required to assess the reasonableness. While Title 23 CFR Part 772 does not serve as design standards, the noise reduction design goals establishes the requirements for noise abatement design that state noise policies have to comply with. In Sec. 772.15 Federal participation of the new regulation, the activities are reorganized into 7 categories instead of 5 categories in the old noise regulation. The approach level of noise is clearly defined as at least 1 dBA less than the NAC, which provides additional clarification to traffic noise impact analysis.

2.2 State Traffic Noise Policies

2.2.1 Participation in Type II projects

The authors have reviewed the traffic noise policies implemented by the U.S. states and territories. All 50 state DOTs, Puerto Rico and the District of Columbia

have updated their noise policies to comply with the new FHWA noise regulation before the mandated date. Based on these state noise policies, it was found that 14 state DOTs have opted to participate in Type II projects. In other words, 28% of state DOTs have participated in Type II projects and 72% of state DOTs do not have Type II programs. Presented in Figure 2.1 are the geographical locations of these 14 states with Type II projects. It is shown that these 14 states are mainly located in three regions, including the west coast, Midwest, and east coast. In the Midwest (15–20), Illinois, Michigan and Ohio have participated in Type II projects. However, Indiana, Wisconsin and Kentucky have opted out of Type II projects. It was also noticed that Wisconsin has established the WisDOT Retrofit Noise Barrier Program that consists of a list of state-funded, stand-alone noise abatement projects on an existing highway, proposed and constructed as identified in the Wisconsin Noise Barrier Study. Some state DOTs, such as Colorado Department of Transportation that used to participate in Type II projects before (21), have suspended Type II program because funding has



Figure 2.1 Geographical distribution of states with Type II programs.

been unavailable. Currently, INDOT does not participate in Type II projects.

2.2.2. Determination of Traffic Noise Impacts

In analysis of the traffic noise impacts from a proposed highway project, state DOTs are required by the new FHWA noise regulation to establish specific noise level indicators for traffic noise impacts. Both the new and old FHWA noise regulations provide two indicators when determining traffic noise impacts, i.e., noise approach level and substantial noise increase. In the old FHWA noise regulation, traffic noise impacts were considered to occur when the predicted traffic noise levels approach or exceed the NAC. Each individual state, however, was allowed to define the level at which the predicted noise approaches the NAC and when the noise substantially exceeds at the existing noise level. Accordingly, the noise receivers were identified as “impacted” when the noise level approached the NAC by 1 dBA. For residential areas, the approach level should be 66 dBA except for Oregon (22) and Arizona (23). The former uses 2 dBA and the latter uses 3 dBA approach criterion. In the new INDOT noise policy, “Approach” is defined to be within 1 dBA of the appropriate NAC.

When a receptor is subjected to a substantial noise increase over the existing noise level, the receptor is also considered to be impacted by traffic noise. Different from the old FHWA noise regulation, the new FHWA noise regulation defines a range of 5 dBA to 15 dBA to be a substantial noise increase. Currently, 3 states, including Maryland (24), North Carolina (25) and Tennessee (26), have defined a substantial noise increase that varies between 10 dBA and 15 dBA and depends on the existing noise level. The substantial noise increase becomes larger when the existing noise level becomes higher. However, most state DOTs have selected a unique, constant value between 5 dBA and 15 dBA as the substantial noise increase. Figure 2.2 shows the distribution of the substantial noise increases adopted

by state DOTs. The minimum substantial noise increase is 6 dBA in terms of Leq(h). Approximately, 39.1% of the state DOTs have defined a substantial noise increase of 10 dBA and 50.0% of the state DOTs have defined a substantial noise increase of 15 dBA. In the Midwest region, a substantial noise increase is currently defined as 15 dBA by Indiana and Wisconsin, 10 dBA by Kentucky, Michigan and Ohio, and 14 dBA by Illinois.

2.2.3 Feasibility for Noise Abatement

When a noise abatement measure is being considered to mitigate traffic noise impacts, it shall be evaluated for both engineering feasibility and acoustic feasibility. Engineering feasibility focuses on the concerns on topography, maintenance, drainage, safety and constructability. Topography concern includes considerable changes in elevations between the roadway and impacted noise receivers. Maintenance concern includes necessary accesses for routine pavement maintenance and winter snow control. Safety concern includes structural stability, roadside clear zone and access for handling vehicle crashes. Drainage concern is related to the potential conflict between the noise abatement and drainage facilities. Constructability concern particularly covers the limitation of location and the maximum noise wall height. It was noticed that 19 state DOTs have established a maximum height for noise walls. As shown in Figure 2.3 is the distribution of the maximum noise wall heights defined by these 19 state DOTs. The maximum noise wall heights vary between 14 ft. and 30 ft. The maximum noise wall height is defined as 20 ft. for approximately 37% of the state DOTs, 25 ft. for 26% of the state DOTs, and 30 ft. for 16% of the state DOTs. In the Midwest region, Ohio defines the maximum noise wall height as 25 ft. and the others do not have a maximum wall height limitation. However, all state DOTs in the Midwest consider the noise wall height for acoustic, structural and aesthetic reasons.

Acoustic feasibility deals primarily with the noise reduction. The new FHWA noise regulation requires that at least 5 dBA noise reduction shall be achieved at

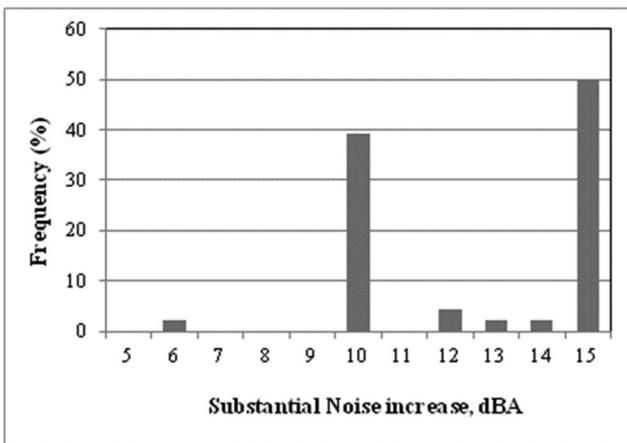


Figure 2.2 Distribution of substantial noise increases by state DOTs.

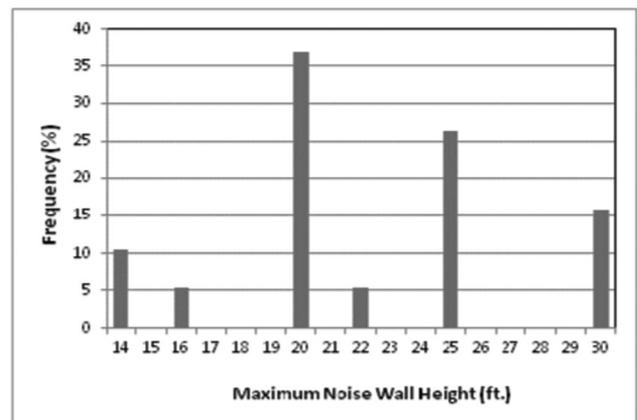


Figure 2.3 Distribution of maximum noise wall heights.

impacted receptors for a noise abatement measure to be acoustically feasible. After reviewing the new noise policies by state DOTs, it was found that all 50 state DOTs, including INDOT, consider a noise abatement to be acoustically feasible if a noise reduction of 5 dBA or greater can be achieved at impacted receptors. The differences arise when determining the impacted receptors. Seemingly, the state DOTs have utilized two main different methods to determine the number of impacted receptors while assessing the acoustic feasibility. The first method is to define a specific number out of the total impacted receptors. Figure 2.4 shows the distribution of the numbers of total impacted receptors considered by 30 state DOTs. To be considered as acoustically feasible, a noise reduction of at least 5 dBA is required for at least 1 impacted receptor by 9 state DOTs (30%), for the majority or (50%+1) of all impacted receptors by 7 state DOTs (23%) and for at least 50% of all impacted receptors by 5 state DOTs (17%). The required noise reduction was at least 7 dBA in the old INDOT noise policy and has been changed to at least 5 dBA in the new INDOT noise policy at more than 50% of impacted receptors.

The second method is to define a specific number from the impacted receptors in the front or 1st row dwelling homes, which has been utilized by a total of 16 state DOTs. As shown in Figure 2.5 is the distribution of the numbers defined by these state DOTs while assessing the acoustic feasibility for a noise abatement measure. A noise reduction of at least 5 dBA is required at 50%+1 of the impacted receptors in the front row by 4 state DOTs (25%), at 60%–80% of the impacted receptors in the front row by 9 state DOTs (56%), and at 50% or more of the impacted receptors in the front row by 3 state DOTs (19%). In addition to the above 46 state DOTs using either the first or second method, 3 state DOTs just specify a noise reduction of at least 5 dBA without defining “impacted receptors.”

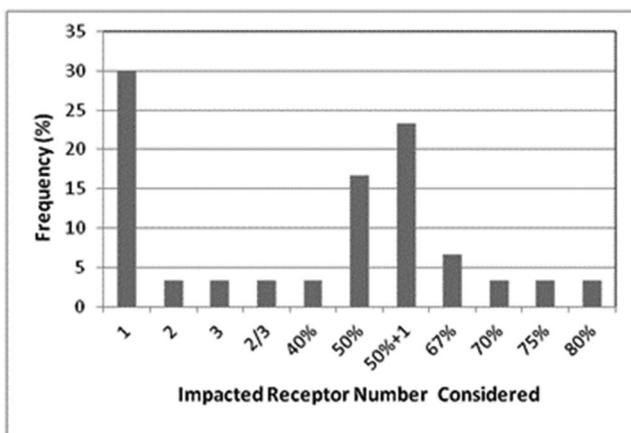


Figure 2.4 Number of impacted receptors for assessing acoustic feasibility.

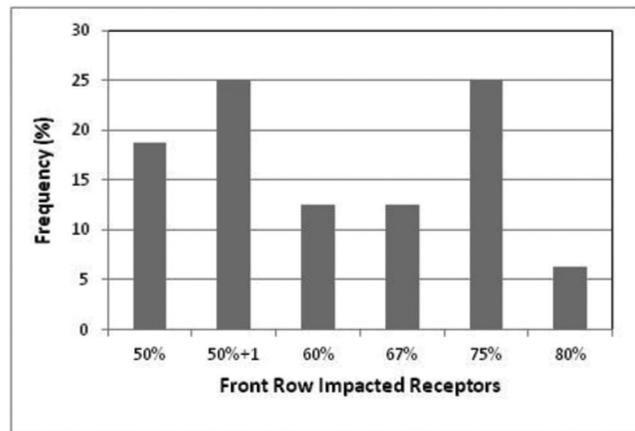


Figure 2.5 Number of front row impacted receptors for assessing acoustic feasibility.

2.2.4 Reasonableness for Noise Abatement

In the new FHWA noise regulation, each individual state DOT is required to determine a baseline cost reasonableness value for FHWA approval. The state DOTs are also encouraged to re-analyze these values on a regular interval not to exceed 5 years. A noise abatement measure shall be cost effective for it to be considered reasonable. While calculating the cost-effectiveness, each individual state DOT is allowed to utilize either the actual construction cost or cost per square foot or the maximum square footage per benefited receptor. Currently, 43 state DOTs, including INDOT, are using the allowable cost per benefited receptor to measure the cost-effectiveness for a noise abatement measure. The lowest allowable cost is \$20,000 per benefited receptor that is defined North Dakota (27) and the maximum allowable cost is \$60,000 per benefited receptor by Hawaii (28). As shown, Figure 2.6 is the distribution of the allowable costs defined by these 43 state DOTs. Approximately, 11 state DOTs (25.6%) defined a cost of \$20,000–\$25,000 per benefited receptor as the allowable cost and 32 state DOTs (74.4%) defined a cost of greater than \$25,000 per benefited receptor as the allowable cost. The average allowable cost is \$35,227 per benefited receptor with an interval of \$32,190 to \$38,264 at a confidence level of 95%. The current INDOT’s allowable cost is \$25,000 per benefited receptor that is the same allowable cost in the old noise policy adopted in 2007. The allowable costs defined by other state DOTs in the Midwest vary between \$30,000 and \$42,500 with an average of \$34,600 per benefited receptor. Apparently, the current INDOT’s allowable cost is much less than not only those by the Midwest states, but also by most of other states nationwide.

Two disadvantages have been identified while using the construction cost per benefited receptor as the cost reasonableness. First, many state DOTs have experienced unprecedented construction cost increases due particularly to the continuing escalation of global fuel prices. The use of construction cost could neither reflect

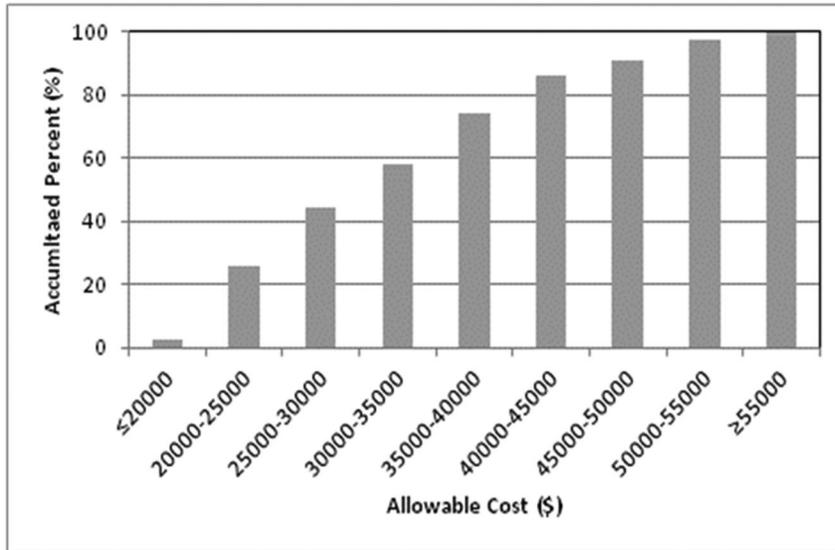


Figure 2.6 Distribution of allowable costs by forty-three state DOTs.

the actual costs for construction materials, labor and equipment, nor reflect the possible effect of inflation. Second, like many other state DOTs, INDOT has several districts. Each district may have localized markets, prices and shortages of materials and skilled labors. Therefore, the construction costs may vary from district to district and may not apply statewide consistently. To overcome the above disadvantages, 7 state DOTs have utilized the maximum square footage per benefited receptor to measure the cost-effectiveness of a noise abatement measure, as shown in Figure 2.7. The maximum square footage varies between 1000 ft² and 2700 ft² per benefited receptor, which is greater than 833 ft² obtained by dividing the cost-effectiveness

of \$25,000 by the bid process of \$30 per square ft. in the current INDOT traffic noise policy.

Another factors used to assess the overall reasonableness of a noise abatement measure is the so-called noise reduction design goal. The new FHWA noise regulation mandates a noise reduction design goal between 7 dBA and 10 dBA at benefited receptors. The determination of benefited receptors may be similar to or different from the determination of impacted receptors for assessing acoustic feasibility. Figure 2.8 shows the distribution of noise reduction design goals established by all 50 state DOTs. It is obvious that most state DOTs (72.0%) define a noise reduction design goal of 7 dBA. Seven state DOTs (14.0%) define a noise

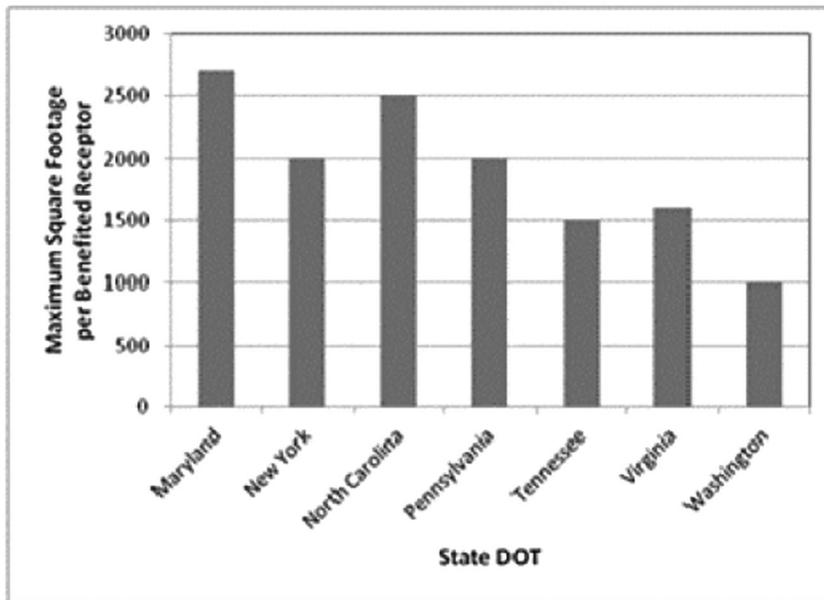


Figure 2.7 Maximum square footages defined by seven state DOTs.

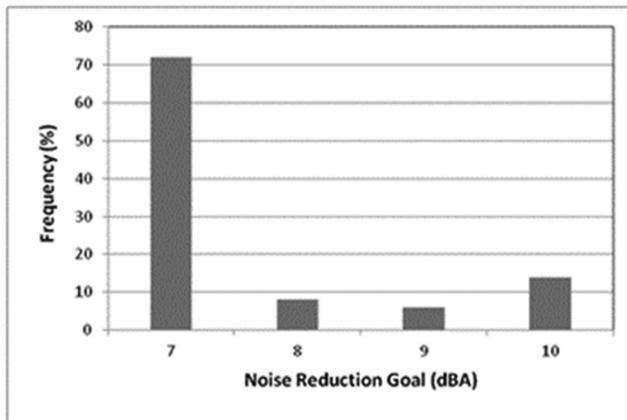


Figure 2.8 Distribution of noise reduction goals by state DOTs.

reduction design goal of 10 dBA. In the Midwest, Indiana, Kentucky, Michigan and Ohio define 7 dBA as the noise reduction design goal. In addition, Michigan requires a noise reduction design goal of 10 dBA for at least 1 benefited receptor. The noise reduction design goal is 8 dBA for Illinois and 9 dBA for Wisconsin. It should be noted that the FHWA noise regulation does not serve as the design standard for designing noise abatement measures. However, the noise reduction design goal does affect the design of noise abatement measures, such as type and height of noise wall.

2.2.5 Third Party Funding

In the FHWA noise regulation, third party funding cannot be used to reduce the cost of the noise barrier in order to meet the reasonableness criteria for Type I Federal-aid projects. Third party funding can only be used to pay for additional features, including landscaping, aesthetic treatments, and functional enhancements (sound-absorbing treatment), and access doors, for noise abatement measures already determined to be feasible and reasonable. This also applies to INDOT. However, several state DOTs allow the use of third party funding in some special situations as follows:

- California DOT (Caltrans) (29): Regional transportation planning agencies are responsible for sponsoring retrofit noise abatement projects. However, abatement proposed for construction within the State right-of-way must be approved by Caltrans and therefore must meet certain minimum requirements as described in the noise policy.
- Colorado DOT: Local agency sponsored and privately funded noise abatement can be constructed on Colorado DOT right of way only if the local agency establishes that no other reasonable alternative to the use of public property is available and meets the requirements of the CDOT directives. Other landscape or hardscape features may be constructed with private or third party funding as part of a non-federal aid project that may provide some noise abatement without meeting the feasible and reasonable determination.

- Illinois DOT: “Non-standard” noise wall designs, such as alternative patterns for a concrete wall, may be considered, but any costs exceeding that of a “standard” noise wall must be funded by the local sponsor.
- Maryland MDSHA: 20% local jurisdiction is allocated for Type II.
- North Carolina DOT: If a local government insists on the provision of a noise abatement measure deemed not reasonable by North Carolina DOT, an abatement measure may be installed provided the local government assumes 100% of the costs and obtains an encroachment permit from North Carolina DOT to perform the work. These costs include, but are not limited to, preliminary engineering, actual construction and maintenance. In addition, local governments must ensure that NCDOT’s material, design and construction specifications are met. The local government must also assume 100% of the liability associated with the measure and hold harmless the NCDOT.
- Ohio DOT (30): Earmark funds have been used for Type II projects on interstates and local expressways in a very rare occurrence. Notice that Earmark funds are not third party funds and come out of the state’s allocation of federal-aid funding.
- Oregon DOT (22): State and local funding may be provided in response to noise complaints through Oregon DOT’s non-federally funded Retrofit Program. If the benefited residents and property owners agree to pursue abatement, they may seek approval to form a Local Improvement District or another means to raise sufficient funds. The local residents, property owners, and the Oregon DOT Region office must agree on the method used to arrange local agency participation. The cost-sharing agreement must be in place and signed by all parties before Oregon DOT will participate in detailed noise impact and abatement analysis.
- Rhode Island DOT (31): If a municipality insists on providing a noise abatement measure deemed unnecessary by Rhode Island DOT, arrangement may be made for the use of Rhode Island DOT’s right of way, provided that the local community is willing to assume 100% of the cost of the abatement measure, including but not limited to preliminary engineering, construction and maintenance.
- Utah DOT (32): The Department may construct and maintain noise abatement measures along state highway right-of-way in cases where citizens, adjacent property owners, developers, or local municipalities provide the cost for the noise abatement, and the abatement meets the other feasible and reasonable criteria. The Department will design, build, and maintain the abatement measure, and the local municipality acting for and on behalf of other groups will pay the Department for all preliminary engineering, construction and maintenance costs.
- Washington DOT (33): In cases where abatement is not reasonable, local agencies or improvement districts may also elect to fund the total amount for the noise abatement provided that the local agency or improvement district maintain all aspects of the abatement (e.g., graffiti control, repairs) per local agreement with Washington DOT, and there is no cost to the state or federal government.
- Wisconsin DOT: Third party funding is allowed on Wisconsin DOT Retrofit Projects (state-funded) if the noise abatement measure would require additional

funding from the third party to be considered feasible and/or reasonable.

Three findings can be made from the above policies on the use of third party funding for abating traffic noise below:

- Third party funding is mainly used to construct noise abatement measures within the State right-of-way.
- Third party funding is mainly used to construct noise abatement measures for either Type II projects or retrofit projects.
- In cases where is not eligible for federal-aid funding for noise abatement, and other groups, including local government and residents, insist on providing a noise abatement measure, other groups must assume 100% of all costs, including pre-engineering cost, construction cost, and maintenance cost under an agreement signed by the state DOT and the local municipality acting for other groups.
- The noise abatement measures must meet the state DOT's material, design and construction specifications.

3. CONSTRUCTION, COSTS, AND STRUCTURAL EVALUATION

3.1 Noise Study Sites

3.1.1 I-465/Keystone Ave. Interchange Improvement Project

I-465 is a beltway of approximately 52 miles circling Indianapolis, the state capital city of Indiana. The I-465/Keystone Avenue Interchange is located in the suburb of the city of Carmel on the northeast side of Indianapolis. The I-465/Keystone Avenue Interchange improvement project is one of the major projects under the Major Moves program and was funded through both federal and state fund source. The work scope of

this project included adding two through travel lanes in each direction (both east and west), reconstructing the interchange bridge and lamps, placing new pavements, upgrading drainage facilities, and installing concrete noise barrier walls. This project was completed with all lanes open to traffic in October, 2011 (see Figure 3.1).

3.1.2 Noise Sensitive Areas

In the pre-engineering process, a field traffic noise impact analysis was conducted for Section 1 of this project, i.e., from Meridian Street to Keystone Avenue (34). The land uses in the project area were grouped into a series of numbered Noise Sensitive Areas (NSAs). The noise levels were found to range from 58.3 dBA to 75.2 dBA and the design year, i.e., 2030, build noise levels were found to range from 59.9 dBA to 78.6 dBA. Based on the INDOT noise policy issued in 2007, this project was identified to have traffic noise impacts in the project area. The feasibility and reasonableness of noise barriers were also evaluated at all locations in the project area where noise impacts were identified under the future build alternative. As a result, two feasible and reasonable noise walls were identified under Type I Program, one in NSA2 located on the north side of I-465 from Monon Trail to Westfield Boulevard and the other in NSA3 located on the north side of I-465 between Monon Trail and College Avenue (see Figure 3.2). Both NSA2 and NSA3 are residential areas (Activity Category B). The former consists of numerous residential homes and a church activity field, the latter consists of an apartment complex and a city park.

NSA1 is located on the south side of I-465 between Westfield Boulevard and Haverstick Road, consisting of a residential development (Activity Category B). Because this area is a less-dense residential area, a noise



Figure 3.1 Aerial photo of improved I-465/Keystone Avenue Interchange (Courtesy of INDOT Office of Environmental Services) (1).

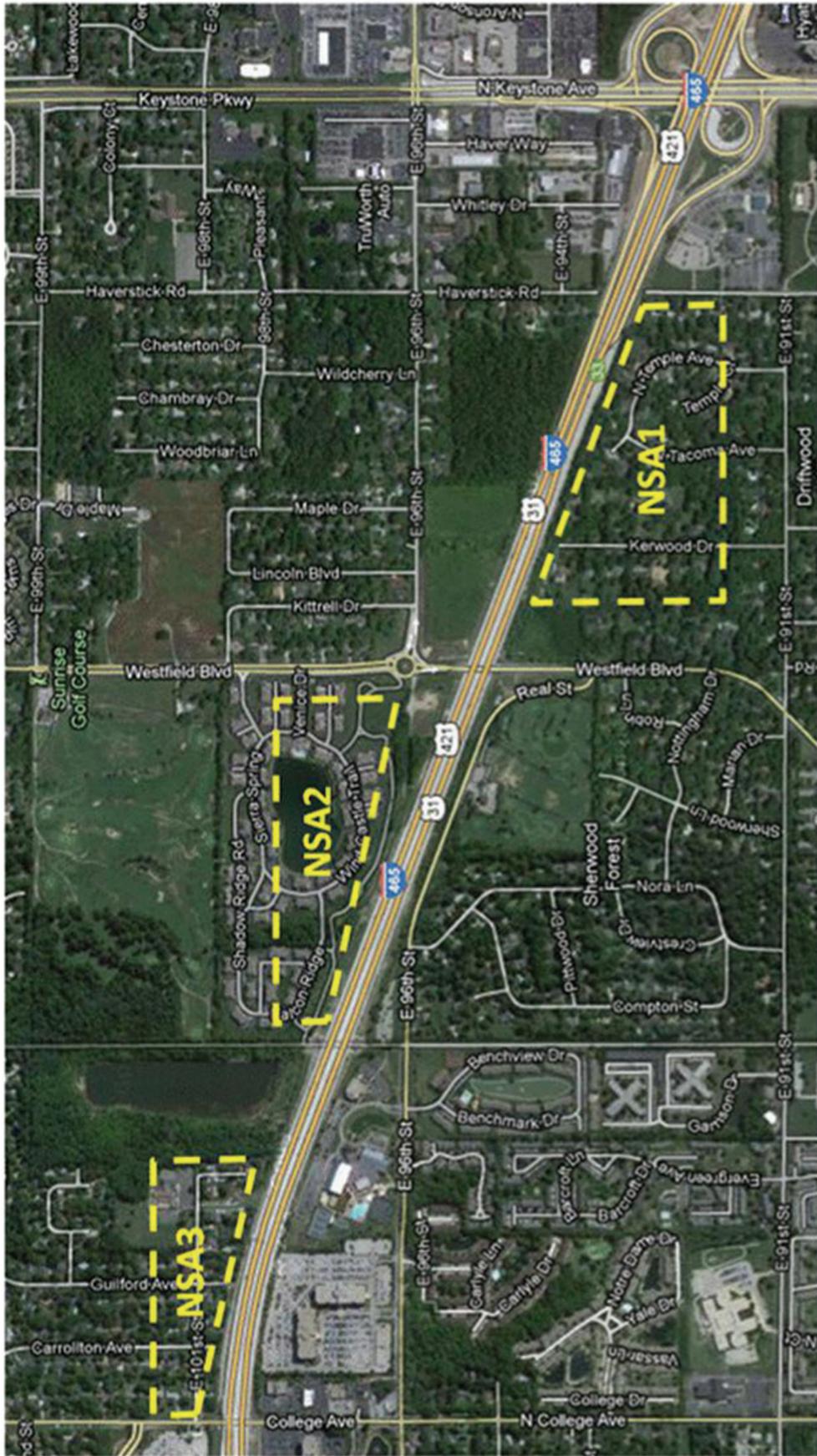


Figure 3.2 Graphical illustration of noise sensitive areas.

wall was found to be neither reasonable nor feasible, and therefore was not justified for receiving federal aid. As a result, the residents in NSA1 were not satisfied. To improve the residents' satisfaction, this study opted to install LOS walls in NSA1 to shield the residential homes from the traffic noise from I-465. The LOS walls along with the conventional concrete noise walls in NSA2 and NSA3 served as the study sites for INDOT not only to compare the acoustic properties of different noise walls, but also to investigate less expensive alternatives for abating traffic noise in less-dense areas where federal funds are not justified. In addition, the pre- and post-installation surveys were conducted to gauge residents' satisfaction with the performance and aesthetics of different wall materials. Research findings will be considered by INDOT in future noise policy revisions and help INDOT better realize the return from its investment in noise barriers from taxpayer dollars.

3.2 Selection of Noise Walls

3.2.1 Field Investigations

In order to identify possible types of LOS walls, field investigations were conducted across Indiana and in Columbus, Ohio. During the field investigations in

Indiana, a total of 14 noise wall sites were screened to identify noise wall materials, surface treatments, visual appearances (shape, pattern, color and texture), and potential problems. Noise levels were measured right in front of and right behind at each noise wall site to assess the acoustic performance of the noise wall. As shown in Figures 3.3, 3.4 and 3.5 are the photos of the typical noise walls taken during the field investigations, including precast concrete, metal, brick and masonry block noise walls. These noise walls are the basic types of noise walls that have been used on the public roads in Indiana. Another type of noise wall that is not presented in the above figures is the combination wood and concrete noise wall originally installed on I-69 in Fort Wayne.

The metal noise walls are made out of steel panels. There are two typical metal noise walls in Indiana, including horizontal and vertical panel orientations (see Figure 3.3). The horizontal panel walls were constructed in 1989 and the vertical panel walls were constructed in 1992. For both horizontal and vertical panel walls, the metal panels are corrugated panels with painted surface. The surface textures were created using a roll-formed mechanical device. Holes and dents were observed in the metal walls. This indicates that the metal noise walls are more vulnerable to impacts of rocks and errant vehicles. Protection guardrails should be provided in front of metal walls even though the

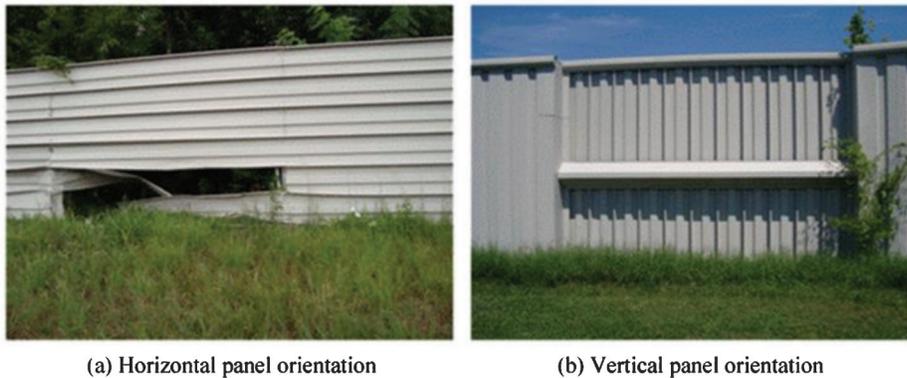


Figure 3.3 Steel noise walls (I-164, Evansville).

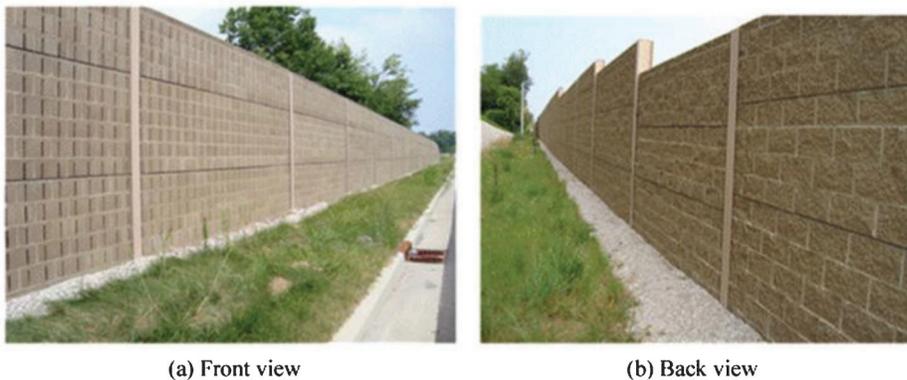
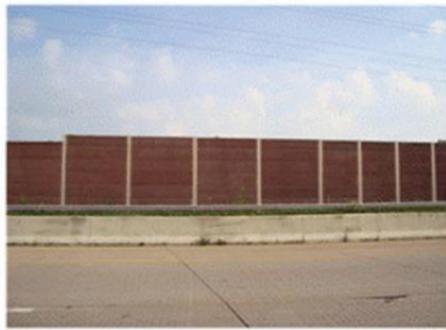


Figure 3.4 CMU noise walls (SR-66, Newburgh and I-465, Indianapolis).



(a) US-20 (South Bend)



(b) I-65 (Sellersburg and Indianapolis)



(c) I-465 (Indianapolis)

Figure 3.5 Typical precast concrete noise walls in Indiana.

metal walls are located outside the roadside clear zone. The masonry block noise walls are commonly made out of concrete masonry block units (CMUs) as shown in Figure 3.4. Each CMU consists of a closed-top and two vertical slots on its front surface. This unique design allows each CMU to expose its inner cavity and better absorb sound waves. The CMUs have a split-face in the back which provides visual appealing textures to the residents behind the CMU walls.

Precast concrete noise wall, namely the conventional concrete noise wall in this study, is probably the most common noise wall currently used in Indiana due to its versatile advantages over other types of noise walls. Precast concrete noise wall is durable in most highway environments and its properties rarely deteriorate in harsh weather conditions. As shown in Figure 3.5, precast concrete noise walls can be designed and fabricated in different shapes, colors, and surface treatments. This provides the flexibility for designers or owners to consider the surrounding natural topographical feature, architecture theme, and local culture. The use of sound absorptive surface treatments can further reduce noise levels and possible sound reflection.

Presented in Table 3.1 are the noise walls screened and the corresponding noise measurements. The noise levels, i.e., Back Noise and Back noise, were measured in front of and behind each noise walls. In “Distance” column, the numbers over and below the slash line are

the distances of the noise receiver from the noise wall while measuring noise levels in front of and behind the noise wall, respectively. The determination of distances was solely based on the presence of natural and man-made obstacles. It is shown that the noise levels behind noise walls are significantly less than those in front of noise walls. The average noise reduction is 15.6 dBA, 16.1 dBA, and 20.4 dBA for steel, CMU and precast concrete noise walls, respectively. The combination wood and concrete noise wall also achieved a noise reduction of 21.9 dBA.

The authors also conducted field investigations in Columbus, Ohio, and interviewed ODOT’s engineers. Figure 3.6 shows the noise walls observed on I-270 and I-70, including acrylic, wood, metal, brick, precast concrete, and fiberglass walls. Also, ODOT engineers made multiple valuable comments on the performance of noise walls used in Ohio. Precast concrete walls commonly use absorptive surfaces. Fiberglass walls cost as much as the precast concrete wall and the acrylic wall was two times as expensive as the precast concrete wall if a same noise reduction is to be achieved. Metal walls are vulnerable to the impacts of rocks and errant vehicles and require protection guardrails. Wood walls are prone to weathering, resulting in gaps and therefore reduced acoustic performance. Also, ODOT experimented with a vegetation wall consisting of bags of soil with sprouting plants and grass. It was found that the vegetation wall was not UV-stable and the

TABLE 3.1
Noise Barrier Walls and Noise Measurements

City	Road	Barrier Material	Height (feet)	Distance (feet)	Front Noise (dBA)	Back Noise (dBA)
Evansville	I-164	Steel	14	6/6	76.9	63.0
Evansville	I-164	Steel	14	6/6	77.3	62.5
Evansville	I-164	Steel	9	7/20	73.4	55.2
Fort Wayne	I-69	Wood/Concrete	14	7/15	78.9	57.0
Newburgh	SR-66	CMU	—	7/7	70.3	56.4
Indianapolis	I-465	CMU	—	7/7	83.1	64.8
Fort Wayne	I-69	Precast Concrete	15	6/6	79.5	57.9
Sellersburg	I-65	Precast Concrete	17	5/5	81.5	58.5
Indianapolis	I-65	Precast Concrete	15	5/5	76.2	58.2
South Bend	US-20	Precast Concrete	—	10/10	83.7	65.9
Indianapolis	I-465	Precast Concrete	15–17	7/7	72.7	56.1
Indianapolis	I-465	Precast Concrete	15–17	7/7	85.4	59.4
Indianapolis	I-465	Precast Concrete	15–17	7/7	87.7	68.0
Indianapolis	I-465	Precast Concrete	15–17	7/7	83.1	65.7



(a) Transparent wall



(b) Wood wall



(c) Metal wall



(d) Brick wall



(e) Precast concrete wall



(f) Fiberglass wall

Figure 3.6 Typical noise walls in Columbus, Ohio.

maintenance, particularly watering to keep the plants alive, is costly.

3.2.2 Noise Wall Materials

The INDOT standard specifications (35) require that sound barrier systems shall be ground mounted and designed to achieve a sound transmission loss equal to or greater than 20 decibels at all frequencies when tested in accordance with ASTM E 90. For Type I, single-sided absorptive, sound barrier systems and have a minimum noise reduction coefficient of 0.70 on the roadway side. As a result of a cooperative effort between the contractor and INDOT staff, Hebel AAC, Noise D-Fence, and Sanders precast panels were selected for the LOS noise walls in NSA1 to achieve greater noise reductions at the same cost. The Armtec's Durisol precast concrete noise barriers were selected as the conventional noise wall in NSA2 and NSA3. Figure 3.7 shows the photos of these four wall systems.

Durisol precast noise wall panels are made out of organic softwood shavings processed to an acoustically engineered size and bonded together under pressure with Portland cement concrete (PCC) (36). They are also claimed to be highly sound absorptive, non-combustible, thermally insulating, self-draining and freeze-thaw resistant. Hebel AAC noise wall panels are made out of Hebel Autoclaved Aerated Concrete (37). An acrylic coating is applied to the surface of AAC panel. The Hebel AAC noise panels are claimed

to be low maintenance, weather resistant, and environmentally safe. Noise D-Fence noise wall panels consist of highly resilient expanded polystyrene foam. They are claimed to be highly durable, resistant to water, fungal and weathering, and requires no maintenance such as painting and cleaning (38). The Sanders precast noise wall panels are made out of acoustic concrete mix bonded together with Portland cement concrete mix (39).

Table 3.2 shows the acoustic properties of the above noise barriers. The absorptive noise barriers such as Durisol precast, Noise D-Fence and Sanders precast barriers provide a noise reduction coefficient (NRC) greater than 0.70. Their sound transmission class (STC) ratings are 46, 29 and 46, respectively. The AAC wall is a reflective wall with a STC rating of 50. It is well known that NRC indicates the amount of sound energy absorbed upon striking a particular surface and STC rates the barrier's ability to resist airborne sound transfer at 16 standard frequencies ranging from 125 Hz to 4000 Hz (40). First, NRC is the average of the sound absorption at four octave frequencies such as 250, 500, 1000 and 2000 Hz and does not provide information on the sound absorption at both low and high frequencies. Second, two materials with the same NRC rating may not perform the same. Third, NRC does not consider the field installation variables. Therefore, there is a tendency to replace the NRC with the sound absorption average (SAA). SAA is also a single number for rating how absorptive a material.



Figure 3.7 Photos of conventional noise wall and LOS walls.

TABLE 3.2
Acoustic Properties of Selected Noise Walls

Type of Barrier Panel	Surface Treatment	Panel Density (lbs/ft ²)	ASTM C 423 NRC/SAA	ASTM E 90 STC
Durisol Precast	Absorptive	39.6	0.85/0.82	46
AAC	Reflective	25.0	N.A.	50
Noise D-Fence	Absorptive	2.6	0.75/0.73	29
Sanders Precast	Absorptive	20.5	0.75/0.74	46

Nevertheless, it is the average of the sound absorption at twelve 1/3 octave frequencies between 200 and 2500 Hz. A material with a great NRC may have a low STC. Therefore, an effective noise wall should have great NRC and STC.

3.3 Design, Construction, and Costs of Noise Walls

3.3.1 Design and Construction

Presented in Table 3.3 are the dimensions of all noise walls evaluated in this study and the corresponding noise wall panels. The design of the conventional concrete noise walls (Durisol precast concrete noise wall) in NSA 2 and NSA3 were made according to the noise reduction design goal through the standard design procedure. However, the design of the LOS walls, particularly height and length, was mainly based on the engineering judgment. The initial height for the LOS walls, including AAC, Noise D-Fence and Sanders, was 6 ft. (slightly above the average human eye level) to provide some noise reduction. Afterwards, the height of LOS walls was raised to 10–12 ft. to provide more noise reduction without increasing the total bid price. The start and end points of the LOS walls were determined in light of field condition so as not to block the access for roadside maintenance activities. Figure 3.8 shows the layouts of the noise walls in NSA1, NSA2 and NSA3.

Since the LOS wall was the first of its kind in Indiana, a special provision of the sound wall specifications was developed for the design and construction of such a wall system which consist of foundations, vertical support posts, barrier panels, and other wall units (41). The LOS wall plan was made by following the general dimensions of the wall envelope as shown on the plans. The top of the noise wall was designed to be at or above the profile line. Changes in

elevation were accomplished by stepping the panel sections with steps not exceeding 2 ft. vertically. Caisson footings, vertical support posts and connections for ground mounted barrier were designed as specified by the manufacturer. The noise wall system was designed to withstand wind pressure as applied perpendicular to the barrier, in each direction. The construction of the LOS noise walls is similar to the construction of the conventional precast concrete noise wall. Figure 3.9 shows the photos taken in the different construction stages.

Holes for footings were drained of free water prior to placing foundation. Cast-in-place concrete foundation was placed in accordance with the specifications. The steel posts were embedded in concrete with bottom cover of 8 in. \pm 4 in. The integrity of wall was to ensure that no light would be visible through any joint between panels, between post and panel, and between the bottom of barrier wall and the adjacent ground. The depth of holes for footings is 15 ft. for all four noise walls. Clear distance of at least 3 ft. was ensured between the noise wall and the right-of-way (ROW) and between the noise wall and the W-beam guardrail for maintenance activities. For the conventional precast concrete noise walls in NSA2 and NSA3, the post spacing is 15 ft. For the LOS walls in NSA1, The post spacing is 240 in., 170 in., and 180 in. for AAC, Noise D-fence, and Sanders noise walls, respectively.

3.3.2 Cost of Construction

The construction cost of noise wall was broken down to three pay items by INDOT, including barrier design and layout, barrier panels, and panel erection (see Table 3.4). The item, “barrier panels”, consists of the costs for materials and shipping for barrier panels, posts, and foundation preparation and construction. For the Durisol noise wall, the three pay items account for 2.8%, 75.8%, and 21.4% of the total cost,

TABLE 3.3
Dimensions of Noise Walls and Panels

Site	Panel Type	Panel Dimension	Wall Dimension (ft.)	
			Length	Height
NSA1	AAC	19'8"L \times 2'H \times 8"W	800	10–12
	Noise D-Fence	14'L \times 4'H \times 4"W	694	10
	Sanders Precast	15'L \times 4'H \times 7"W	674	10
NSA2/NSA3	Durisol Precast	15'L \times 3'H \times 8"W	5204	10–23



Figure 3.8 Graphical illustration of three noise sensitive areas (NSA1, NSA2, and NSA3).



(a) Clearing and grading



(b) Drilling hole



(c) Placing foundation and post



(d) Installing barrier panels

Figure 3.9 Photos of construction of noise walls.

respectively. For the LOS walls, the three pay items share on average 10.1%, 62.9%, and 27.0% of the total construction cost, respectively. The unit costs for LOS walls were more expensive than the Durisol noise walls. This is probably due to two main reasons. First, competitive bids were not available because of the small amount of the work of LOS walls. Second, the foundation for the conventional precast concrete noise walls was utilized for the LOS walls due to the lack of experiences. To further evaluate the variations of the construction cost of noise wall over time, this study reviewed the data, including the dimension and construction cost, on the noise walls constructed in the past two decades as shown in Table 3.5.

Four observations can be made through careful inspection of the data in Table 3.5. First, on average, the steel panel noise wall demonstrates the lowest

construction cost and the unspecified concrete noise wall demonstrates the highest construction cost. The combination wood/concrete noise wall is cheaper than other types of concrete noise walls. The construction cost of the concrete precast panel noise wall is close to that of the CMU block noise wall. Second, the regional cost differences of construction of noise walls are not evident within the State. This may indicate that it is not necessary for INDOT to implement a tiered approach to cost reasonableness statewide. Third, the construction costs of noise walls, overall, have demonstrated an increasing tendency with time. However, the construction costs of noise walls have experienced fluctuations over the past two decades. The authors discounted the construction costs of the precast concrete noise walls to the present values, i.e., the value in 2010, at a discount of 3% and 4%, respectively (see Figure 3.10).

TABLE 3.4
Noise Walls and Construction Costs

Type of Noise Wall	Type of Barrier Panel	Cost Breakdown (\$/ft ²)			Total Cost (\$/ft ²) (2011)
		Design & Layout	Barrier Panels	Panel Erection	
LOS*	ACC	\$3.00	\$18.00	\$8.00	\$29.00
	Noise D-Fence	\$3.00	\$18.80	\$8.00	\$29.80
	Sanders Precast	\$3.00	\$19.00	\$8.00	\$30.00
Conventional**	Durisol Precast	\$0.66	\$17.72	\$5.00	\$23.38

*Prices based on 5,000 sq ft.

**Prices based on the actual area of 83339 sq ft.

TABLE 3.5
Noise Barrier Walls and Noise Measurements

City	Road	Material	Type	Year	Length (ft)	Height (ft)	Costs (\$/ft ²)*
Evansville	I-164	Steel	I	1989	4700	9	\$14.59
Evansville	I-164	Steel	I	1992	2573	14	\$20.44
Fort Wayne	I-69	Wood/Concrete	I	2004	34521	14	\$18.03
Gary/Lake	I-80	Wood/Concrete	I	2004	3400	15	\$21.89
Gary/Lake	I-69	Wood/Concrete	I	2004	2996	16	\$21.89
Hammond/Gary	I-80/I-94	Concrete/Unknown	II	1995	33000	16	\$31.51
St. Joseph	US-20	Concrete/Unknown	I	1999	5100	15	\$39.55
Fort Wayne	I-69	Concrete Precast	I	2007	21853	15	\$16.42
Hammond	I-80/I-94	Concrete Precast	I	1997	14648	15	\$27.63
South Bend	US-20	Concrete Precast	I	1997	8554	18	\$24.07
Sellersburg	I-65	Concrete Precast	I	2007	6322	17	\$33.92
Indianapolis	I-65	Concrete Precast	I	2007	10080	15	\$35.41
Indianapolis	I-465	Concrete Precast	I	2006	5900	15	\$37.18
Indianapolis	I-465	Concrete Precast	I	2006	900	17	\$67.35
Indianapolis	I-465	Concrete Precast	I	2007	13662	15	\$33.18
Indianapolis	I-465	Concrete Precast	I	2008	4715	14	\$30.79
Indianapolis	I-465	Concrete Precast	I	2008	4271	14	\$30.88
Indianapolis	I-465	Concrete Precast	I	2008	2213	17	\$30.56
Indianapolis	I-465	Concrete Precast	I	2008	5006	13	\$29.79
Indianapolis	I-465	Concrete Precast	I	2008	5449	18	\$29.62
Indianapolis	I-465	Concrete Precast	I	2008	1888	15	\$30.20
Indianapolis	I-465	Concrete Precast	I	2008	1291	17	\$30.62
Indianapolis	I-465	Concrete Precast	I	2009	2878	12	\$29.68
Indianapolis	I-465	Concrete Precast	I	2009	2153	14	\$29.00
Indianapolis	I-465	Concrete Precast	I	2009	1922	15	\$30.81
Indianapolis	I-465	Concrete Precast	I	2009	2908	15	\$30.71
Indianapolis	I-465	Concrete Precast	I	2009	4273	14	\$29.39
Indianapolis	I-465	Concrete Precast	I	2009	4976	13	\$29.25
Indianapolis	I-465	Concrete Precast	I	2009	1786	12	\$30.04
Indianapolis	I-465	Concrete Precast	I	2009	3389	20	\$30.18
Indianapolis	I-465	Concrete Precast	I	2010	4251	15	\$33.73
Indianapolis	I-465	Concrete Precast	I	2009	4900	12	\$29.09
Indianapolis	I-465	Concrete Precast	I	2009	2090	17	\$29.69
Indianapolis	I-465	Concrete Precast	I	2009	5660	12	\$29.74
Indianapolis	I-465	Block	I	2009	1000	12	\$29.06
Indianapolis	I-465	Block	I	2009	4100	14	\$29.87
Newburg	SR-66	Block	I	2010	765	13	\$30.00

*Costs in 2007.

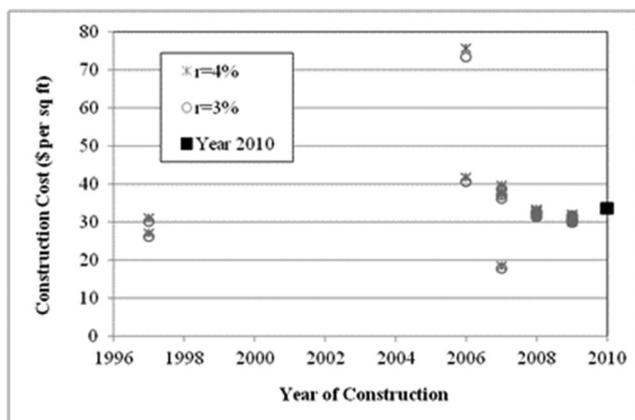


Figure 3.10 Discounted noise wall construction costs (2010 Value).

Seemingly, a discount rate of 4% can better reflect the true inflation in the construction costs of noise walls.

The fourth observation is that the amount of work of the noise wall may affect its construction cost significantly, particularly for a very small project or a very large project using precast concrete panels. For the precast concrete noise wall of 900 ft. long installed in 2006, the construction is \$67.35/ft². For the precast concrete noise wall of 21853 ft. long installed on I-69 in Fort Wayne in 2004, the construction cost is \$16.42/ft². Figure 3.11 shows are the 2011 present values of the construction costs of the precast concrete and CMU block noise walls and the areas of corresponding noise walls. For most of the noise walls, the construction costs varied over a range of \$30/ft² to \$40/ft². Without including the above two (very small and very large) projects, the construction costs of the noise walls fall within a range of \$32.60/ft² to \$35.06/ft² at a confidence

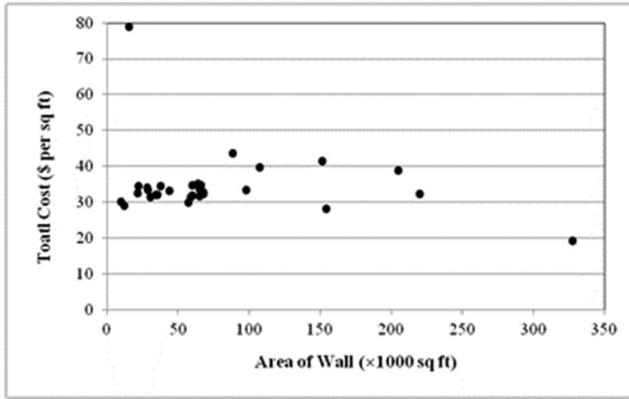


Figure 3.11 Variation of construction cost with noise wall area.

level of 95%. Therefore, it is recommended that when determining the cost-effectiveness for precast concrete and CMU block noise walls, an estimated cost of \$34 per square foot of barrier should be used in Indiana. At present, no sufficient data is readily available for the authors to determine the maximum square footage per

benefited receptor to measure the cost-effectiveness of noise wall for INDOT.

3.4 Evaluation of Noise Wall Condition

3.4.1 Initial Surface Condition

The colorings and coatings of LOS noise walls are required by INDOT to have a minimum predicted maintenance free lifespan of 10 years. In order to evaluate the initial surface conditions of the Durisol conventional precast concrete noise wall and LOS walls, visual inspection was conducted right after the completion of noise wall construction to identify possible surface defects, such as chips, spalls, uneven surfaces, and surface color fading due to weathering and ultra violet rays from the sun. Figure 3.12 shows the close-ups of the surfaces of the conventional precast noise and LOS walls.

Basically, all these four noise walls demonstrated satisfactory surface conditions in terms of integrity and color. No visible surface defects, such as chipping, spalling, cracking and color fading, were observed



(a) Durisol



(b) AAC



(c) Noise D-Fence



(d) Sanders

Figure 3.12 Close-ups of surfaces of noise walls.

except for one portion of the Noise D-Fence walls. As shown in the photo in Figure 3.7, waviness can be observed in the outer skin on one portion of the Noise D-Fence wall. It was claimed that by the vendor, the waviness occurred purely due to the result of the stiffener placement, and any waviness of the outer skin can be eliminated through making the longitudinal stiffeners continuous to better support the outer skin of the panel.

3.4.2 Initial Structural Conditions

INDOT also requires that all noise barrier materials shall have a minimum predicted maintenance free structural lifespan of 20 years. In order to evaluate the initial structural integrity of these noise walls, the ground penetration radar (GPR) testing was conducted right after the completion of installation of each noise wall using a 1.6 GHz ground coupled GPR antenna with a vertical resolution of 512 samples per trace and a horizontal resolution of 48 scans per foot. It is well known that GPR utilizes pulsed electromagnetic waves to map changes in the electrical properties of the subsurface. For a nonconductive nonmagnetic material, the propagation of the radar wave is determined by the dielectric constant. The dielectric constant of air is 1, the dielectric constant of water is 80, and the dielectric constant of concrete is around 8. Consequently, the presence of water in a material is expected to raise the dielectric constant of a material.

In addition, changes in the dielectric constant of a material over time may be linked to the possible deterioration of materials, debonding of steel rebar, and presence of voids. Furthermore, there are accepted protocols for evaluating the condition of reinforcement in bridge decks with GPR, which could be used to evaluate reinforcement of the sound walls in some cases. It should be pointed out that, however, the interpretation of GPR data is not a pure science and relies to a great extent on the successful experience. While the GPR testing has been reported to be utilized to identify possible cracking, mass loss, volume inconsistency and debonding of steel rebar inside a structural member, extreme care should always be exercised in drawing conclusions between GPR data and structural defects. So far, no report has been published on the evaluation of structural condition of noise barrier using GPR testing, particularly the delamination between acoustic mix and regular concrete mix in a noise barrier panel, such as the Durisol and Sanders precast barrier panels.

Presented in Figure 3.13 are the cross-sections and reinforcements of the four noise barrier panels. The Durisol panel consists of a reinforced regular concrete mix core and Durisol mix layers on both side of the concrete mix core. The AAC panel consists of a board of ACC mix with two layers of reinforcements and an acrylic surface coating. The Noise D-Fence panel consists of a core board made of expanded polystyrene foam (EPS), fiberglass sheeting, EPS stiffeners, and

metal track cap. The fiberglass sheeting is glued to the EPS board and stiffeners, respectively. The shear forces in the fiberglass sheeting are transferred to the metal perimeter track. The cavities between the stiffeners are filled with absorptive materials, i.e., non-woven fibers. The Sanders panel consists of acoustic mix on the front and regular concrete mix in the back with reinforcement.

The maximum amplitudes of amplitude envelope of the traces were examined, because there is no direct method of determining the dielectric constant from the ground coupled GPR data and the maximum of amplitude envelope is strongly inversely correlated with the dielectric constant. Therefore, high maximum amplitude envelope values indicate low dielectric constants. Several observations may be made on the differences in the sound wall panels through examining the raw GPR data, i.e., the amplitudes of reflected radar wave as shown in Figures 3.14, 3.15, 3.16, and 3.17. First, the reinforcement is visible in the Durisol, AAC and Sanders precast panels. Second, the amplitudes in Figure 3.14 demonstrate greater variations in color and band width than those in Figures 3.15, 3.16 and 3.17 in the horizontal direction. This may indicate that the AAC, Noise D-Fence and Sanders panels are more homogenous than the Durisol panel probably due to the grooves and large pores in the absorptive surface of the Durisol panel. Third, for each of noise barrier panels, the amplitudes demonstrate relatively consistent patterns in terms of color and band width. This indicates that at this time, each panel has consistent dielectric properties in the horizontal and thickness directions, respectively.

Presented in Figure 3.18 are the plots of the amplitude envelope maximums for each of the four noise barrier panels. The Noise D-Fence panel demonstrated the lowest dielectric constant followed by the Sanders precast panel. The vertical bumps in the amplitude envelope plot of the AAC panel were caused by the GPR coupling with the near surface reinforcement. The vertical bumps in the amplitude envelope plot of the Durisol panel were probably caused by the air contained in the grooves in absorptive surface. It is believed that any changes in the amplitude envelope maximum over the life of the panel may indicate possible deterioration of material and bonding inside the panel. In addition, the amplitudes of the GPR wave returned off the steel rebar, as shown in Figure 3.19, may be utilized to evaluate the condition of the rebar contained in the panel. The sinusoidal wave on the top is the ground coupled pulse. For example, the return off the top reinforcement layer in the AAC panel is included as part of the ground coupling of the antenna, and therefore, the amplitude of the return off the lower layer of reinforcement could be utilized. Furthermore, the any visible changes in the amplitude over time may indicate changes of material dielectric properties, and therefore possible deterioration inside the panel.

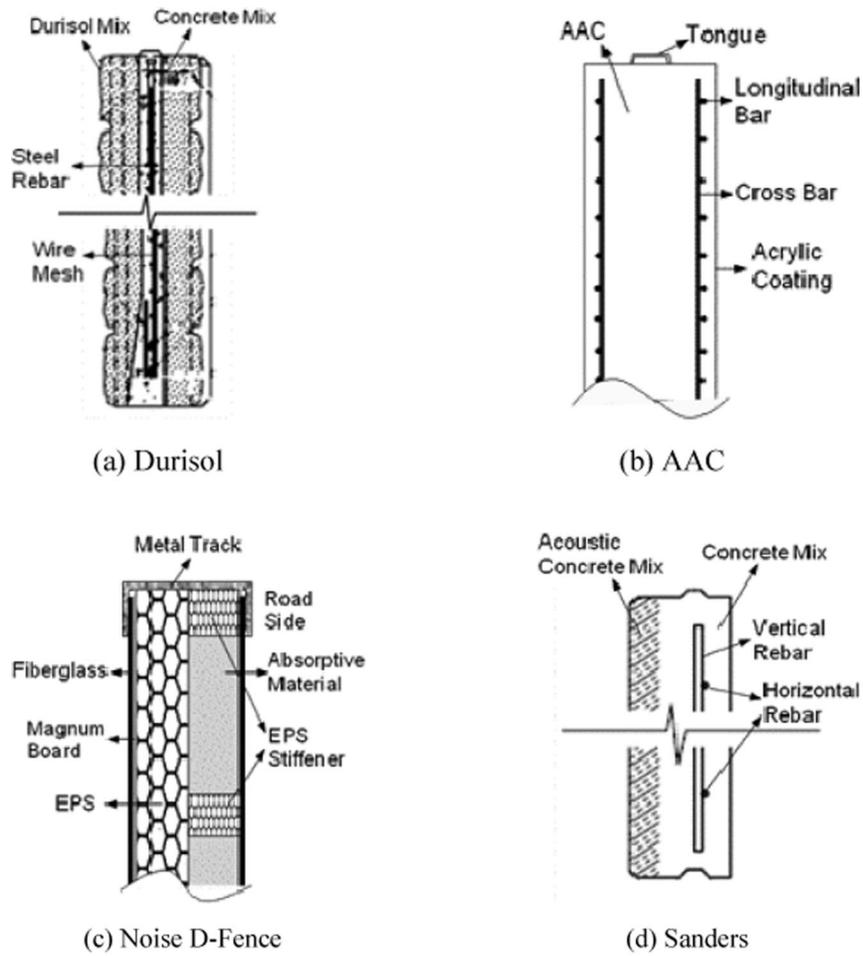


Figure 3.13 Cross-sections and reinforcements.

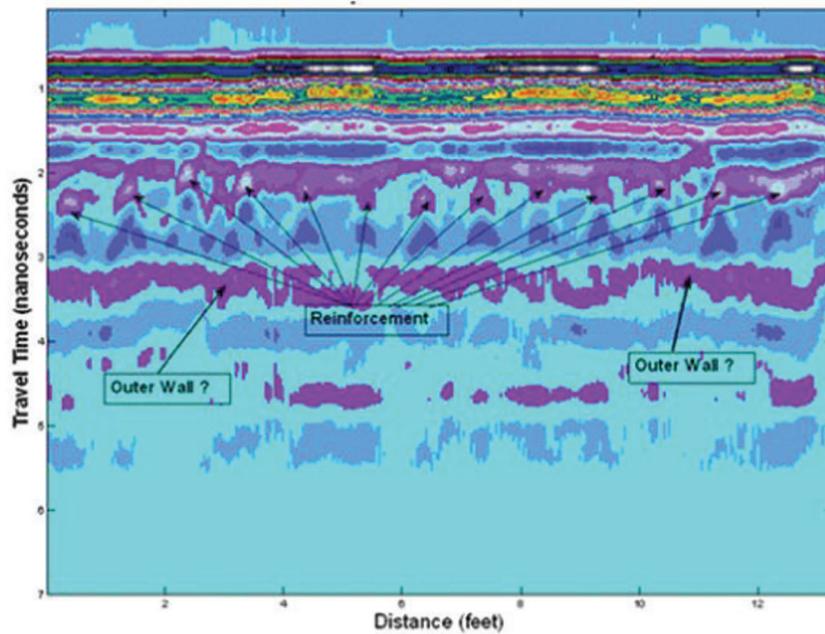


Figure 3.14 Typical GPR data collected on Durisol precast noise barriers.

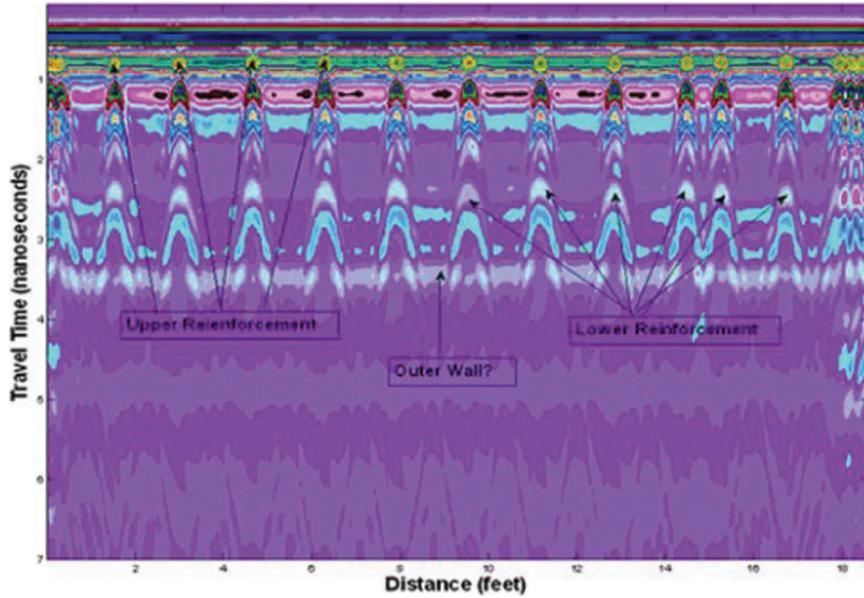


Figure 3.15 Typical GPR data collected on AAC noise barriers.

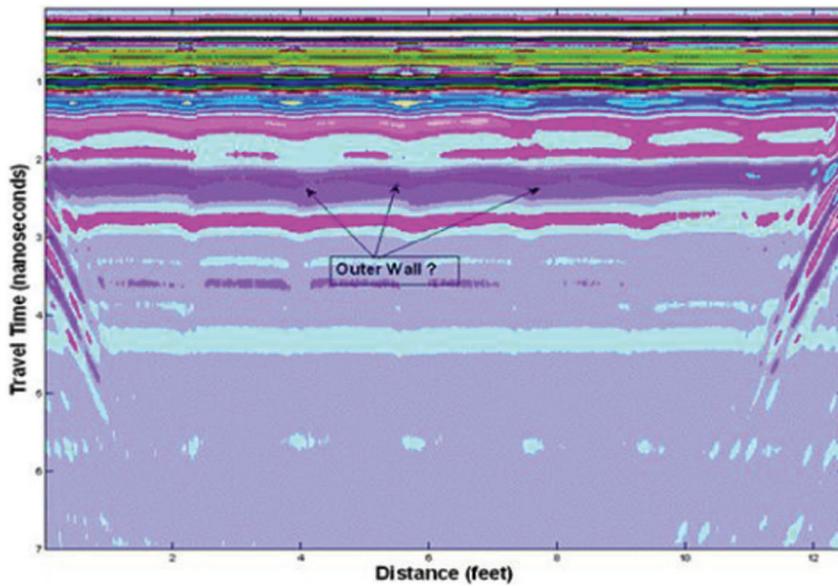


Figure 3.16 Typical GPR data collected on Noise D-Fence noise barriers.

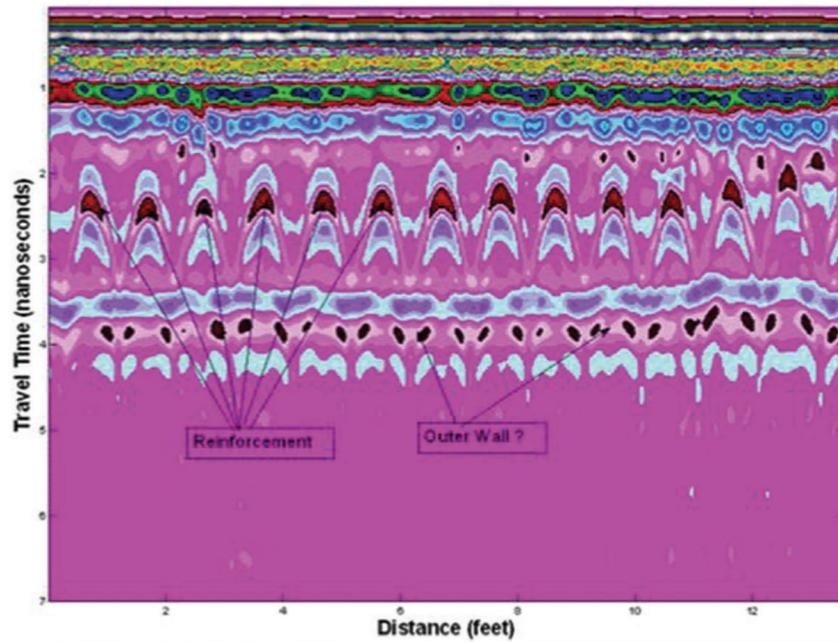


Figure 3.17 Typical GPR data collected on Sanders noise barriers.

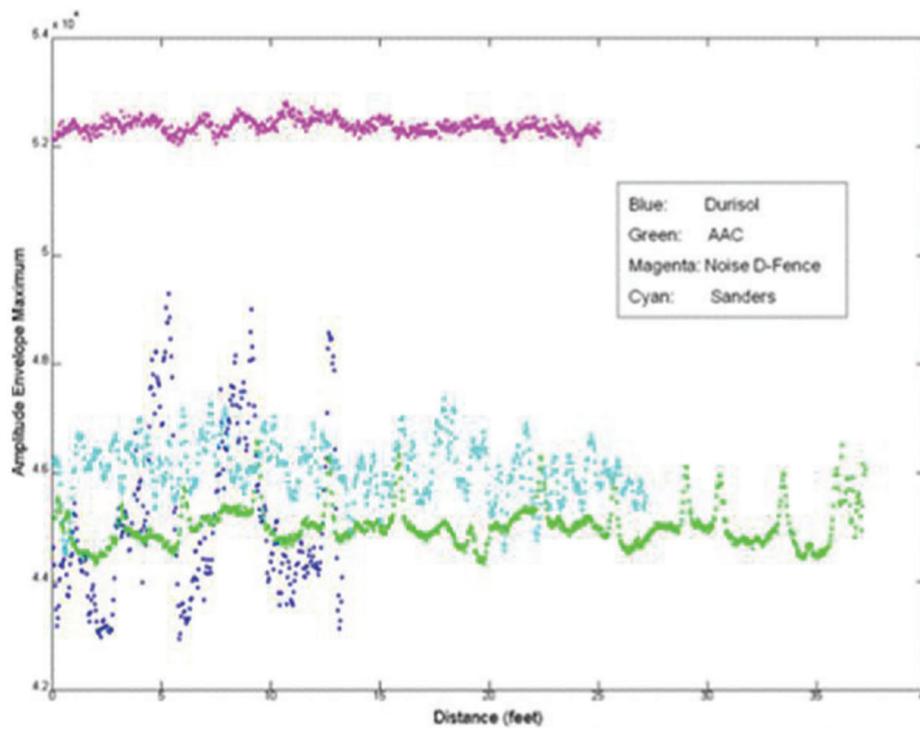


Figure 3.18 Amplitude envelope maximums.

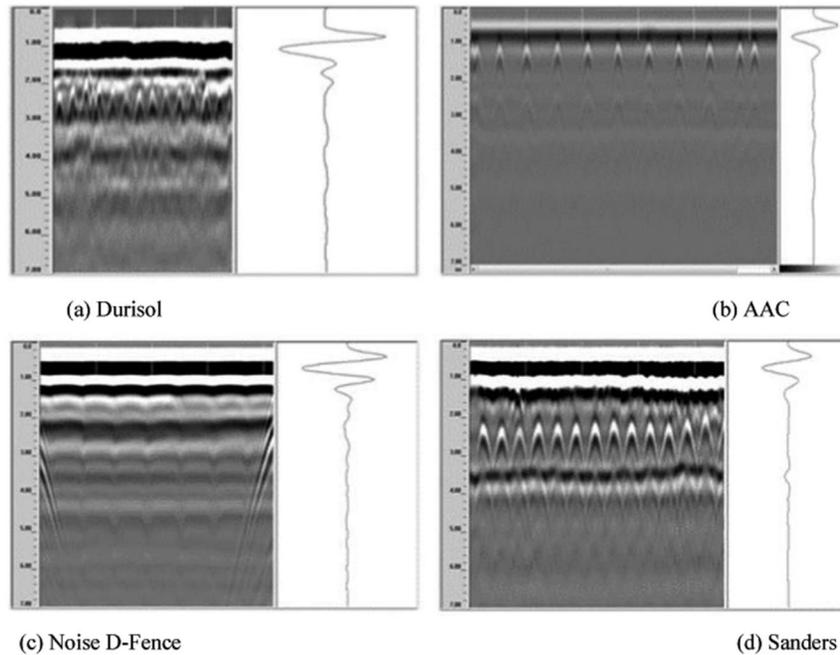


Figure 3.19 Variation of amplitude of reflected radar wave in thickness direction.

4. PRE- AND POST-INSTALLATION FIELD NOISE LEVELS

4.1 Field Noise Testing

4.1.1 Locations of Noise Measuring Sound Meters

As described in Chapter 3, the project area was divided into three noise study sites, i.e., three noise sensitive areas, including NSA1, NSA2 and NSA3 in light of their land use. In reality, these three noise sensitive areas were initially defined in a previous study (33), and were further modified to be utilized in this study for providing continuity between these two studies and for the purpose of reference. These three noise sensitive areas are all located within 800 feet of I-465 with the following geographical features:

- NSA1 is located on the south side of I-465 between Westfield Boulevard and Haverstick Ave. It contains numerous residential homes. The elevations of the land and pavement surface on I-465 are very close near Haverstick Ave. The land in the middle of this area is lower than the pavement surface of I-465. Most lands between I-465 and residential homes are shielded with trees and grasses. The LOS noise walls, including AAC, Noise D-Fence and Sanders Precast noise walls, are installed in this area.
- NSA2 is located on the north side of I-465 between Westfield Boulevard and Monon Trail. It contains an apartment complex and a city park, along with several tree zones, and one earth berm (in the west part). The ground in this area is generally flat. The elevation of this area is lower than the elevation of pavement surface on I-465. The city park is located in the opening area close to Westfield Boulevard. The conventional concrete noise

walls made of Durisol precast panels are placed in this area.

- NSA3 is also located on the north side of I-465, but between Monon Trail and College Avenue. This area consists of numerous residential homes, a church activity field, and one commercial property. This area demonstrates flat topography shielded with trees and grasses. The ground level in this area is much lower than the pavement surface of I-465. For most residential homes between I-465 and 101st East St., their back and side yards face I-465. NSA3 is also shielded with Durisol precast concrete noise walls.

To determine the locations of noise measuring sound meters, great care was exercised to fulfill the primary goals of this study. As stated earlier, the ultimate goal of the pre- and post-installation noise measurements in this study was to map the overall noise level in each of the noise sensitive areas and identify noise reductions after the installation of the four different noise walls. However, other considerations were also carefully weighed while making decisions. First, the factors, including land activity category, frequent human use, impacted receptors and benefited receptors, were evaluated in accordance with FHWA Guidance. All noise measuring locations were selected within 800 ft. of the centerline of I-465. Second, the physical locations and dimensions of the noise walls were taken into consideration for research purposes, particularly field comparison of the acoustic performance between the four different noise walls. Third, the residents' concerns echoed in the pre- and post-installation community surveys were mainstreamed into the development of field noise testing plan, such as noise receiver locations, test day, and test time.

Field investigations were also conducted to identify the land use, physical features of residential houses and noise wall characteristics. As shown in Figures 4.1, 4.2 and 4.3 are the locations of noise test sound meters in pre- and post-installation noise testing. In NSA1, noise measurements were made at a total of 29 locations, of which, 24 locations were on the south side of I-465 to map the overall noise levels and noise changes before and after installation in the neighborhood, and 5 locations were on the north side of I-465 just for references. In NSA2, 9 locations were selected to map the overall noise levels and noise reductions in the resident area, and 1 location, i.e., Receiver R'10, was used to assess the noise level in the city park. In NSA3, a total of 9 locations were identified to assess the overall noise levels and noise reductions mainly in the

neighborhood. The sound meters were placed in front of the door, window, patio or playground facing I-465. Only R15 in NSA1 was intentionally placed close to the right of way (ROW) in the backyard of a resident's house to assess the possible maximum noise level in the neighborhood.

4.1.2 Noise Measuring

The pre- and post-installation noise measurements were made using the sound level meters that meet ANSI Type I specifications. These sound level meters are equipped with random incidence prepolarized precision condenser microphone, preamplifier and data logging, and can be used for both 1/1 and 1/3 octave-band analysis. During field noise measuring, the sound level



Figure 4.1 Noise measuring locations in NSA1 (LOS walls).

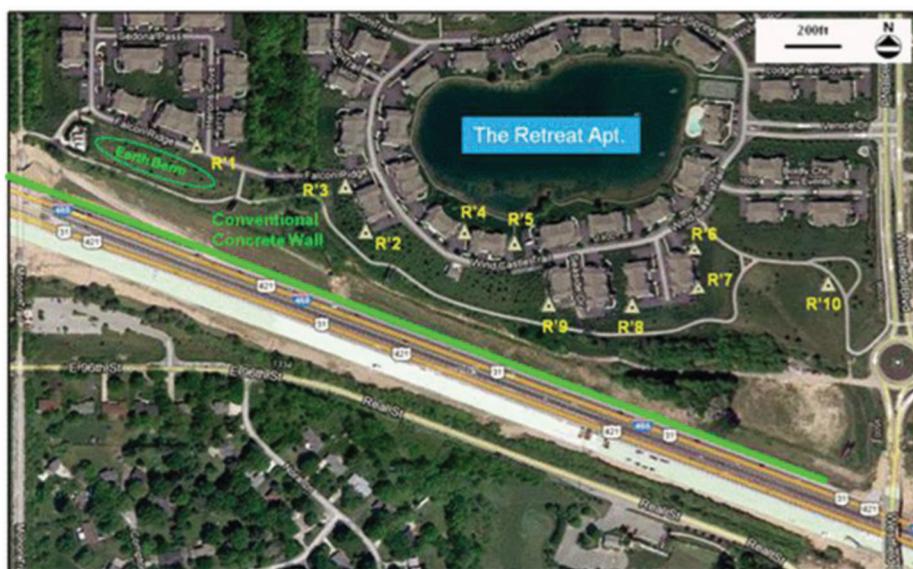


Figure 4.2 Noise measuring locations in NSA2 (conventional noise wall).



Figure 4.3 Noise measuring locations in NSA3 (conventional noise wall).

meters were placed at a height of 5 ft. (41) between the ground and the microphone pointing towards to I-465 as shown in Figure 4.4. At each noise measuring location, a sampling period of 15 minutes was adopted and the equivalent sound level, i.e., Leq , was utilized as the noise descriptor required by FHWA and INDOT. Leq is the equivalent steady-state sound level which in a sampling period contains the same acoustical energy as the time-varying sound level during the same sampling period. $Leq(h)$ is the hourly value of Leq , i.e., the hourly A-weighted equivalent sound level, and represents the energy average of A-weighted sound levels occurring during a one-hour period. Pre- and post-installation noise measurements were typically made in similar meteorological and ground conditions with the wind speed less than 10 mph, clear sky and dry pavement.



Figure 4.4 Placement of sound level meter for noise measuring.

4.2 Pre- and Post-Installation Noise Measurements

4.2.1 Preliminary Noise Analysis

Prior to the formal process of pre-installation field noise data collection, noise levels were measured for preliminary noise analysis to assess temporal noise variations. In reality, hourly noise variations were assessed using the pre-installation noise data collected on June 6-7, 2011. The sound level meter was placed at the location of R28 in NSA1 (see Figure 4.1), which was on the boundary of right of way (ROW). Figure 4.5 shows the noise variations from 6:30 a.m. through 19:30 p.m. Two peak noise levels occurred at 8 a.m. and 5 p.m., respectively. Without the sudden noise drops at 15:30 p.m. and 17:30 p.m., the noise level varied between 77.5 dBA and 79.5 dBA and the maximum difference is 2 dBA. As shown in Figure 4.6 are the hourly traffic distributions at an Automatic Traffic Recorder (ATR) site on I-465, 1 mile on the east of US-31. This segment of I-465 mainly carries commuter traffic for people going to and returning from work, which commonly results in the morning and evening rush hours. It is obvious that both the traffic noise and volume hourly variations exhibit a similar time-of-day pattern. During field testing, the authors observed the noise level fluctuated significantly with trucks, particularly those heavy semi-trailer trucks with whining noise under acceleration.

Figure 4.7 shows the daily noise variations throughout a week. The noise measuring was made at the same location for assessing hourly noise variations, i.e., R28 in NSA1. The noise levels were measured at 7:30 a.m. and 8:30 a.m., respectively, throughout a week in June 2011. The peak noise day occurred on Tuesday in light of Leq at 8:30 a.m., and on Thursday at 7:30 a.m. The lowest noise level occurred on Sunday regardless of the measuring time. On weekdays, the noise levels varied

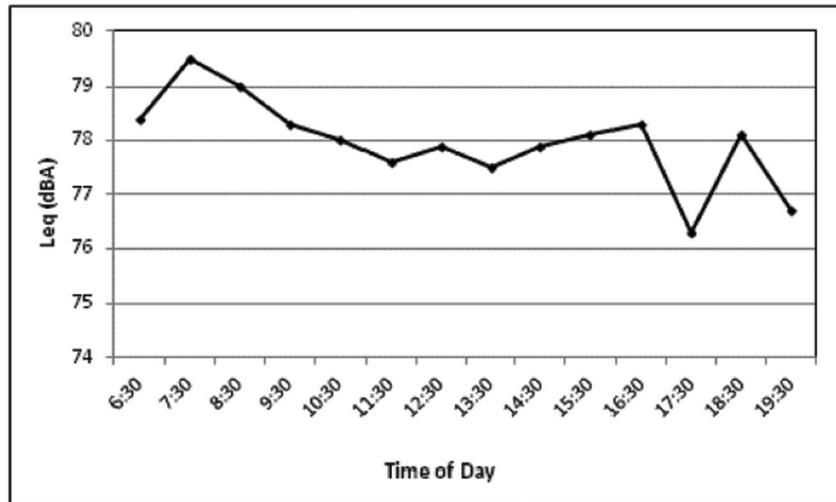


Figure 4.5 Hourly pre-installation noise variations in NSA1.

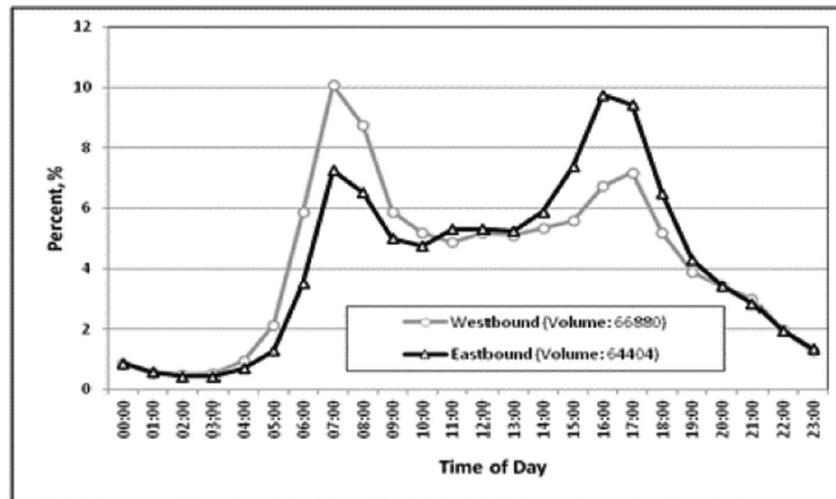


Figure 4.6 Hourly traffic distribution in NSA1.

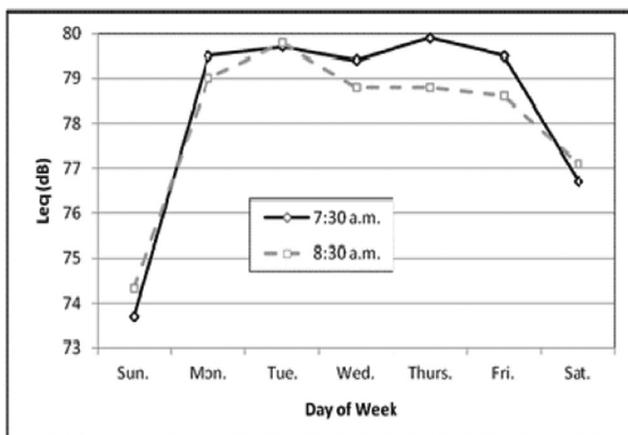


Figure 4.7 Daily noise variations throughout a week in NSA1.

between 79.4 dBA and 79.9 dBA at 7:30 a.m. and between 78.6 dBA and 79.8 dBA at 8:30 a.m. The maximum noise difference is 1.2 dBA over 5 weekdays. The above observations about the temporal noise variations can be extended to conclude that the hourly noise variations may not be perceptible during the daytime in the NSA areas and the daily noise variations may be negligible over weekdays. In other words, there should be no noticeable differences in the noise measurements regardless of the time of day and day of week (weekdays) when the noise measurements are taken. Consequently, the pre- and post-installation noise levels were measured commonly between 9:00 a.m. and 16:00 p.m. when the pavement was dry and the wind speed was less than 10 mph for research purposes. Special noise measurements were also made during peak noise hours to address the residents' concerns.

4.2.2 Noise Measurements

Presented in Tables 4.1, 4.2, and 4.3 are the pre- and post-installation noise measurements and associated noise reduction (NR) values in the three NSA areas, respectively. In NSA1 with the three LOS walls, the pre-installation noise measurements were made at residential houses on Haverstick Ave., Temple Ave., and Kerwood Dr. on May 9 (Monday) and 11 (Wednesday), 2011. The noise measurements made on the north side of I-465, including R4, R5, R6, R7, and R29 and the noise measurement at R28 on the south of I-465, which are located outside the neighborhood boundaries, are not included in Table 4.1. Notice that the pre-installation noise level at R1 is 68.1 dB, which is greater than the pre-installation noise level at R2, 67.5

dBA. This may contradict the basic principles of sound propagation since location of R1 is much farther (approximately 190 ft.) from I-465 than the location of R2. It was thought that the traffic on the ramp and the ground condition might play a role in this. Since the noise variations were negligible over weekdays as shown in Figure 4.7, the computed noise reductions should reflect the actual situation.

In NSA2, i.e., the Retreat Apartment with conventional concrete walls made of Durisol precast panels, the pre-installation noise measurements were made on May 5, 2011, and the post-installation noise measurements made on July 23, 2012. The apartment units selected for noise testing are mainly Wind Castle Trail and Castle Woods Cove. Receiver R'1 was placed in front of a unit on Falcon Ridge behind an earth berm.

TABLE 4.1
Neighborhood Noise Levels in NSA1 (LOS Walls)

Receiver ID	Address	Pre-Installation Noise Level (dBA)	Post-Installation Noise Level (dBA)	NR (dBA)
R1	9180 Haverstick Rd.	68.1	55.9	12.2
R2	9220 Haverstick Rd.	67.5	60.9	6.6
R3	9240 Haverstick Rd.	68.6	66.0	2.6
R8	2450 Temple Ct.	56.8	50.6	6.2
R9	9211 N Temple Ave.	55.5	51.9	3.6
R10	9241 N Temple Ave.	61.2	57.2	4.0
R11	9261 N Temple Ave.	67.2	64.2	3.0
R12	9265 N Temple Ave.	70.3	67.0	3.3
R13	9266 N Temple Ave.	63.0	60.5	2.5
R14	9269 N Temple Ave.	67.7	63.7	4.0
R15	9273 N Temple Ave.	71.7	66.5	5.2
R16	9277 N Temple Ave.	71.6	65.3	6.3
R17	9280 N Temple Ave.	61.7	58.4	3.3
R18	9311 N Temple Ave.	69.9	64.7	5.2
R19	9314 N Temple Ave.	63.8	59.2	4.6
R20	9310 N Tacoma Ave.	64.3	57.8	6.5
R21	9311 N Tacoma Ave.	64.4	58.5	5.9
R22	9350 Kerwood Dr.	59.4	56.0	3.4
R23	9351 Kerwood Dr.	57.9	54.7	3.2
R24	9401 Kerwood Dr.	63.2	60.0	3.2
R25	9402 Kerwood Dr.	62.9	57.9	5.0
R26	9449 Kerwood Dr.	70.9	65.7	5.2
R27	9450 Kerwood Dr.	68.3	62.8	5.5

TABLE 4.2
Neighborhood Noise Levels in NSA2 (Conventional Concrete Walls)

Receiver ID	Address	Pre-Installation Noise Level (dBA)	Post-Installation Noise Level (dBA)	NR (dBA)
R'1	1160 Falcon Ridge	66.7	63.4	3.3
R'2	1381 Wind Castle Trail	71.5	64.2	7.3
R'3	1411 Wind Castle Trail	69.1	61.2	7.9
R'4	1450 Wind Castle Trail	68.2	61.2	7.0
R'5	1486 Wind Castle Trail	66.1	59.7	6.4
R'6	9671 Castle Woods Cove	63.2	57.8	5.4
R'7	9713 Castle Woods Cove	67.0	62.4	4.6
R'8	9720 Castle Woods Cove	68.5	62.8	5.7
R'9	9722 Seaside Dr.	73.2	65.6	7.6
R'10	Public Park	64.7	61.9	2.8

TABLE 4.3
Neighborhood Noise Levels in NSA3 (Conventional Concrete Walls)

Receiver ID	Address	Pre-Installation Noise Level (dBA)	Post-Installation Noise Level (dBA)	NR (dBA)
R"1	9826 Cornell Ave.	66.0	62.1	3.9
R"2	9839 Cornell Ave.	60.5	58.0	2.5
R"3	941 East 101 St.	66.1	62.5	3.6
R"4	931 East 101 St.	66.8	64.0	2.8
R"5	9975 East 101 St.	66.0	60.8	5.2
R"6	9978 East 101 St.	65.1	59.4	5.7
R"7	10102 Carrolton Ave.	64.6	62.3	2.3
R"8	10095 Guilford A	65.5	61.5	4.0
R"9	10085 Guilford A	69.2	63.4	5.8

Receiver R'10 was placed in the public park, roughly 210 ft. from the Westfield Blvd. and 370 ft. from the Retreat Apt. boundaries. In NSA3 also with conventional concrete walls made of Durisol precast panels, the pre- and post-installation noise levels were measured on October 24, 2011 and July 23, 2012, respectively. The noise measurements were used solely to assess the noise levels at residential houses located between East 101 St. and I-465. The noise measurements at R"7 in front of 10102 Carrolton Ave., were made to address the concern raised by the residents over the possible noise increase due to noise diffraction, i.e., the bending of sound waves over the top of noise wall after the completion of construction.

4.3 Pre- and Post-Installation Noise Analysis

4.3.1 Pre- and Post-Installation Noise Levels

It is shown that in Tables 4.1, 4.2, and 4.3, all selected resident homes received certain noise reductions,

regardless of the noise sensitive area. Table 4.4 shows the statistical summaries of the noise measurements, including both descriptive and special statistics in NSA1, NSA2, and NSA3, respectively. In NSA1, the pre-installation noise levels at all 23 homes varied between 55.5 dBA and 71.7 dBA with an average noise level of 65.0 dBA. After the installation of LOS walls, the noise levels dropped to 50.6-67.0 dBA with a reduction of 2.5-12.2 dBA and an average reduction of 4.8 dBA. Approximately, 91.3% of the 23 homes received a noise reduction ≥ 3 dBA and 47.8% of the tested homes received a noise reduction ≥ 5 dBA. For the 11 impacted homes with a pre-installation noise level ≥ 66 dBA, the noise levels decreased from 67.2-71.7 dBA to 55.9-67.0 dBA. The average post-installation noise level is 63.9 dBA and the average noise reduction is 5.4 dBA. Also, 63.6% of the impacted homes received a noise reduction ≥ 5 dBA or more.

For the 8 homes in the front row, the average pre- and post-installation noise levels are 69.9 dBA and 65.2 dBA, respectively. The average reduction is 4.7 dBA with 62.5% of the 8 homes receiving a noise reduction

TABLE 4.4
Statistical Summaries of Noise Measurements

Receiver ^a	Statistics	NSA1 ^b (LOS Walls)			NSA2 ^c (Conv. Crete Wall)			NSA3 (Conv. Crete Wall)		
		Pre-Inst	Post-Inst	NR.	Pre-Inst	Post-Inst	NR	Pre-Inst	Post-Inst	NR
All	# of Homes	23	23	23	9	9	9	9	9	9
	Min, dBA	55.5	50.6	2.5	63.2	57.8	3.3	60.5	58.0	2.3
	Max, dBA	71.7	67.0	12.2	73.2	65.6	7.9	69.2	64.0	5.8
	Ave, dBA	65.0	60.2	4.8	68.2	62.0	6.1	65.5	61.6	4.0
	% of Homes with NR ≥ 3 dBA			91.3	—	—	100	—	—	67.0
	% of Homes with NR ≥ 5 dBA			47.8	—	—	77.8	—	—	33.3
Impacted	# of Homes	11	11	11	8	8	8	5	5	5
	Min, dBA	67.2	55.9	2.6	66.1	59.7	3.3	66	60.8	2.8
	Max, dBA	71.7	67.0	6.6	73.2	65.6	7.9	69.2	64	5.8
	Ave, dBA	69.3	63.9	5.4	68.8	62.6	6.2	66.8	62.6	4.3
	% of Homes with NR ≥ 5 dBA			63.6	—	—	75.0	—	—	40.0
1 st Row	# Homes	8	8	8	8	8	8	6	6	6
	Min, dBA	68.6	63.7	2.6	66.1	59.7	3.3	65.1	60.8	2.8
	Max, dBA	71.7	67.0	6.3	73.2	65.6	7.9	69.2	64	5.8
	Ave, dBA	69.9	65.2	4.7	68.8	62.6	6.2	66.5	62	4.5
	% of Homes with NR ≥ 5 dBA			62.5	—	—	75.0	—	—	50.0

^aAll=All homes; Impacted=Homes with noise level ≥ 67 dBA; and 1st Row=Homes located in the front row.

^bR1 is not included (see Table 4.1).

^cR'10 is not included (see Table 4.2).

≥ 5 dBA. The percentages of homes with noise reduction ≥ 5 dBA are very close in terms of both the impacted and front row homes. The LOS walls are acoustically feasible according to the 2011 INDOT Traffic Noise Analysis Procedure, which requires a 5 dBA reduction at a majority (greater than 50%) of the impacted receptors. Notice that INDOT has not established any noise reduction design goal for LOS walls. It was anticipated that by INDOT Construction Management, however, LOS walls may provide a noise reduction up to 5 dBA. Seemingly, the LOS walls installed in NSA1 did fulfill the above noise reduction goal.

In NSA2, the noise levels were measured at 9 apartment homes. The pre-installation noise levels were found to be 63.2-73.2 dBA with an average of 68.2 dBA. The post-installation noise levels varied between 57.8 dBA and 65.6 dBA with an average of 62.0 dBA. After installing the Durisol precast concrete (conventional) noise walls, these homes received a noise reduction of 3.3 to 7.9 dBA, depending on the locations, with an average reduction of 6.1 dBA. All of the 9 homes received a noise reduction of 3 dBA or more and 7 homes (77.8%) received a noise reduction ≥ 5 dBA. For the 8 impacted units, the average pre- and post-installation noise levels are 68.8 dBA and 62.6 dBA, respectively. The average noise reduction is 6.2 dBA with 6 homes (75.0%) receiving a noise reduction ≥ 5 dBA. Approximately, 50% of the impacted first row homes received a noise reduction of at least 7 dBA. This confirms that the conventional concrete noise walls are acoustically feasible for abating traffic noise and meet the noise reduction design goal in NSA2.

In NSA3, the noise levels were measured at 9 residential homes. The pre- and post-installation noise levels varied from 60.5 dBA to 69.2 dBA and from 58.0 dBA to 64.0 dBA, respectively. The average noise levels are 65.5 dBA and 61.6 dBA before and after installing the conventional concrete noise walls, respectively. All post-installation noise measurements are below the NAC, i.e., 66 dBA. The average noise reduction is 4.0 dBA with 6 homes (approximately 66.7%) receiving a noise reduction ≥ 3 dBA and 3 homes (33.3%) receiving a noise reduction ≥ 5 dBA. There were a total of 5 impacted homes. The average noise reduction is 4.3 dBA for these impacted homes. Approximately, 40.0% of the impacted homes received a noise reduction ≥ 5 dBA. For the 6 homes in the front row, the average noise reduction is 4.5 dBA and 3 homes (50.0%) received a noise reduction ≥ 5 dBA. The percentage of homes with noise reduction ≥ 5 dBA is greater in terms of the front row homes than that in terms of the impacted homes.

When NSA2 and NSA3 are combined together, there are 18 tested homes (or units), 13 impacted homes and 14 front row homes. For all tested homes, the average pre- and post-installation noise levels are 66.9 dBA and 61.8 dBA, respectively. The average noise reduction is 5.1 dBA with 15 homes (83.0%) homes receiving a noise reduction ≥ 3 dBA and 10 homes (56.0%) receiving a

noise reduction ≥ 5 dBA. For the impacted homes, the average noise reduction is 5.5 dBA and a total of 8 impacted homes (61.5%) received a noise reduction ≥ 5 dBA. For the front row homes, the average noise reduction is 4.9 dBA and a total of 7 impacted homes (50.0%) received a noise reduction ≥ 5 dBA. As a whole, the conventional concrete walls are acoustically feasible in NSA2 and NSA3. In addition, it is shown that the percentage of homes with noise reduction ≥ 5 dBA is greater in terms of the impacted homes than that in terms of the front homes.

4.3.2 Noise Reductions

Presented in Figure 4.8 are the variations of pre- and post-installation noise levels and corresponding noise reduction (or barrier insertion loss) with the distance between the receiver (house) and the center line of I-465. The distances were determined from Google Map using the Distance Measurement Tool. Apparently, both the pre- and post-installation noise levels demonstrate a similar pattern. As the distance increases, the noise level decreases non-linearly. However, the decrease rate drops as the distance increases. The correlation between the post-installation noise level and distance is more significant than that between the pre-installation noise level and the distance. No clear trend can be observed about the noise reductions. This is probably due to the involvement of more factors, such as noise wall dimension and site situations that will be discussed later.

In order to further examine the noise reductions, Figure 4.9 shows the distribution of noise reductions in NSA1. Careful examination of Figure 4.9 indicates that overall, the noise reduction tends to decrease as the distance increases, particularly in the areas behind AAC and Noise D-Fence walls. However, the noise reductions have no clear trend in the area behind Sanders precast noise wall. In reality, the Sanders precast noise wall ends right on Haverstick Road. There is a free, open field between Haverstick Road and I-465

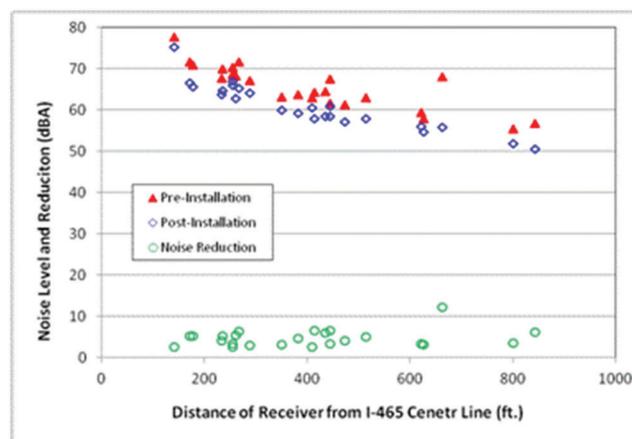


Figure 4.8 Variation of noise level and reduction with distance in NSA1.



Figure 4.9 Distribution of noise reductions in NSA1.

off-ramp to keystone Avenue. The houses on Haverstick Road have a clear line of sight to the eastbound traffic on I-465 and on the off-ramp. As a result, the traffic noise from I-465 between Haverstick Road and the Interchange might have reached the houses at R1, R2 and R3.

Presented in Table 4.5 are the summaries of noise levels and reductions in the areas shielded by different LOS walls. While the noise reduction right behind the Sanders wall is less than that behind the AAC or Noise D-Fence wall, the areas shield by the Sanders, Noise D-Fence, and AAC walls, respectively, received a similar amount of noise reduction that is perceptible to the human ear. There is no evidence to support that the three LOS walls, such as AAC, Noise D-Fence and Sanders Precast walls, demonstrated different acoustic effectiveness.

Figures 4.10 and 4.11 show the distributions of noise reductions due to the installation of Durisol precast concrete (conventional) noise walls in both NSA2 and NSA3, respectively. Three observations can be made by carefully examining the locations of the noise receivers and corresponding noise reductions. First, the noise reduction decreases as the receiver distance increases in both NSA2 and NSA3. Second, the noise reduction in NSA2 is greater than that in NSA3. Third, the receivers

located behind the middle of the noise wall in NSA2 experienced greater noise reductions than those receivers located behind the two ends of the noise wall. IN NSA3, the receivers near College Avenue received greater noise reductions than those near Monon Trail.

4.3.3 Multivariate Correlation Analysis

It is well known that the sound propagation depends mainly on the distance, noise wall dimensions and ground condition. Another factor that has been identified in this study is the elevation difference between the noise source (pavement surface) and the ground surface of the receiver. Table 4.6 shows the noise reduction, observed ground condition, and characteristics of the noise wall at each receiver in NSA2 and NSA3. Again, the distances were measured from Google map. The noise wall heights and elevation differences were determined from the design drawings of cross sections.

The Spearman rank correlation analysis was utilized to assess the potential effects of these factors on the noise levels due to three reasons. First, the Spearman rank correlation analysis makes no assumptions on the distribution of the data. Second, the variable, i.e., distance, noise wall height or elevation difference,

TABLE 4.5
Noise Statistics by Type of LOS Wall

Type of Wall	Shielded Areas	Average Noise Level (dBA)		Average Noise Reduction (dBA)
		Pre-Installation	Post-Installation	
Sanders	Haverstick Rd.	63.6	58.1	5.5
Noise D-Fence	N. Temple Ave.	66.8	62.2	4.6
AAC	Kerwood Dr.	63.8	59.2	4.3



Figure 4.10 Distribution of noise reductions in NSA2.

usually falls within a certain range. The Spearman correlation analysis is less sensitive to the outliers in the data that may be produced from an extreme value of the variable. Third, the noise level is related to these variables monotonically. Table 4.7 shows the Spearman rank correlation coefficient matrices for the noise levels and reductions versus distance, noise wall height and ground elevation.

Before installing the noise walls, the correlation coefficients between noise level and the variables are both negative. This indicates that the pre-installation noise level decreases as the distance or the elevation difference increases. The absolute value of the correlation coefficient between the noise level and elevation difference is greater than that between the noise level and distance, which

implies that the pre-installation noise level is more closely related to the elevation than the distance. After installing the noise walls, the factor of noise wall dimensions was added to the correlation analysis. It is shown that the correlation coefficients between noise level and the variables are all negative. This indicates that overall, the principles of sound propagation remain valid after installing the noise walls. However, the strongest correlation arises between the post-installation noise level and distance, and the post-installation noise level is more closely associated with the noise wall height than the elevation difference. This may imply the effect of noise wall, particularly sound diffraction.

In the case of noise reduction, the correlation coefficient is negative between the noise reduction and



Figure 4.11 Distribution of noise reductions in NSA3.

TABLE 4.6
Characteristics of Noise Walls and Ground Conditions in NSA2 and NSA3

Receiver	Address	Distance (ft.)	Height (ft.)	Elevation Difference (ft.)	Ground Condition
R'1	1160 Falcon Ridge	370.2	11.0	22.0	Earth berm
R'2	1381 Wind Castle Trail	327.0	15.0	7.5	Pine tree row
R'3	1411 Wind Castle Trail	406.9	15.0	7.5	Pine tree row
R'4	1450 Wind Castle Trail	422.3	16.0	4.0	Some short trees
R'5	1486 Wind Castle Trail	442.3	16.0	4.0	Pine tree row
R'6	9671 Castle Woods Cove	639.4	17.0	1.0	Maple tree row
R'7	9713 Castle Woods Cove	514.3	17.0	1.5	Maple tree row
R'8	9720 Castle Woods Cove	411.3	17.0	0	Some pine trees
R'9	9722 Seaside Drive	311.5	17.0	-1.0	Pine tree row
R'10	Gazebo (Park)	655.7	18.0	3.0	Some short trees
R"1	9826 Cornell Ave.	208.9	13.0	8.5	Maple & pine trees
R"2	9839 Cornell Ave.	383.0	13.0	8.5	Maple & pine trees
R"3	941 East 101 St.	231.8	15.0	4.0	Free & tree row
R"4	931 East 101 St.	316.0	16.0	5.0	Maple trees
R"5	9975 East 101 St.	223.8	18.0	12.0	Almost free
R"6	9978 East 101 St.	213.0	20.0	16.0	Some maple trees
R"7	10102 Carrolton Ave.	322.0	20.0	14.0	Maple trees
R"8	10095 Guilford Ave.	318.0	16.0	7.0	Almost free
R"9	10085 Guilford Ave.	149.5	16.0	7.0	Some maple trees

TABLE 4.7
Spearman Rank Correlation Coefficient Matrices

Variable	Distance	Elevation Difference	Height
Pre-Installation Noise Level	-0.1343	-0.3069	—
Post-Installation Noise Level	-0.2897	-0.1709	-0.1732
Noise Reduction	0.0167	-0.3021	0.0004

elevation difference. Nevertheless, the correlation coefficient is positive between the noise reduction and distance or noise wall height. In particular, the correlation coefficient is close to zero between the noise reduction and noise wall height. This may be used to conclude that in the real world, the noise reduction not necessarily always decreases as the distance increases. Also, the effectiveness of noise wall height may become limited. Overall, the correlation coefficients in the three cases are relatively small. In reality, the actual sound propagation in the field is determined by the combined effect of the factors described earlier. However, many of the factors could be accurately measured, particularly the ground elevation, tree row and building row.

5. PSYCHOACOUSTIC-BASED NOISE WALL EFFECTIVENESS EVALUATION

5.1 Current Methods for Evaluating Noise Walls

Many different kinds of materials have been used in building noise abatement walls. For noise abatement walls made out of the same material, they may be built with different heights and shapes due to geographic and/or cost constraints. It is important to quantitatively analyze and study the noise reduction capability of a

noise abatement wall. This would provide policy makers, investors, residents, and general public better understanding of the effectiveness of the sound barriers. More importantly, building a noise abatement wall is an expensive project. Therefore, it is necessary to study and estimate how a noise abatement wall would perform before building it.

Several noise abatement wall effectiveness measuring methods have been developed, of which, insertion loss (42), sound absorption (43), and the European standard CEN/TS 1793-5 (44) have been widely used. Publication FHWA-PD-96-046 (42) describes recommended procedures for highway noise abatement wall insertion loss measurements, which include “direct” before/after measurement, “indirect” before measurement at an equivalent site, and “indirect” predictions of before levels. After ambient adjustment, the insertion loss is determined by:

$$IL_i = (L_{Aref} + L_{edge} - L_{Arec}) - (L_{Bref} - L_{Brec}) \quad (5 - 1)$$

Where, IL_i is the insertion loss at the i^{th} receiver, L_{Bref} and L_{Aref} are the BEFORE and AFTER adjust reference levels, respectively, L_{edge} is the edge diffraction correction factor, and L_{Brec} and L_{Arec} are the BEFORE and AFTER adjusted source levels at the i^{th} receiver, respectively.

For each measurement, the insertion loss is introduced to calculate the effectiveness of a sound as outlined by the FHWA. And in parallel sound barriers, the Noise Reduction Coefficient (NRC), defined as the arithmetic average of the Sabine absorption coefficients, is the way to measure sound barriers.

FHWA Traffic noise model (45) was designed to compute highway traffic at nearby receivers and aid in the design of highway noise abatement walls. It includes FHWA recommended noise emission levels for

different cruise-throttle vehicle types (automobiles, medium trucks, heavy trucks, buses, and motorcycles) on different pavement types (dense-graded asphaltic concrete, Portland cement concrete, open-graded asphaltic concrete, and a composite pavement type consisting of data for DGAC and PCC combines) with different traffic-control devices (stop signs, toll booths, traffic signals, and on-ramp start points). TNM takes several sound propagation factors into consideration: atmospheric absorption, divergence, intervening ground, intervening barriers, intervening rows of buildings, and intervening areas of heavy vegetation. TNM computes the effect of intervening ground with theory-based acoustics.

In ASTM C423-09a, the standard test method for sound absorption and sound absorption coefficients consists of measurement of the sound absorption of a room, measurement of a sound absorption coefficient, and measurement of the sound absorption of an object. The measurement of sound absorption is to calculate the decay rate:

$$A = 0.9210 \frac{Vd}{c} \quad (5 - 2)$$

Where, A is the sound absorption, V is the volume of reverberation room, c is the speed of sound, and d is the decay rate.

Tronchin et al. introduced a measurement of sound barriers using reflection index and sound insulation index (44). Based on CEN/TS 1793-5 standard, reflection index and sound insulation index are used to characterize barriers employed for road traffic noise reduction. The reflection index (RI) is calculated by:

$$RI_j = \frac{1}{n_j} \cdot \sum_{k=1}^{n_j} \frac{\int_{A_{f_j}} |F[t \cdot h_{r,k}(t) \cdot w_r(t)]|^2 \cdot df}{\int_{A_{f_j}} |F[t \cdot h_i(t) \cdot w_i(t)]|^2 \cdot df} \quad (5 - 3)$$

The sound insulation index (SI) for every one-third octave frequency band is obtained by:

$$SI_j = -10 \cdot \log_{10} \left\{ \frac{\sum_{k=1}^n \left(\frac{d_k}{d_i} \right)^2 \cdot \int_{A_{f_j}} |F[h_{t,k}(t) \cdot w_{t,k}(t)]|^2 \cdot df}{n \cdot \int_{A_{f_j}} |F[h_i(t) \cdot w_i(t)]|^2 \cdot df} \right\} \quad (5 - 4)$$

Their experimental results show their proposed “in-situ” method can achieve better performance than both the sound intensity measurements and the traditional tests performed in the lab. However, all of above methods have several limitations:

- These models do not provide detailed frequency analysis of noise characteristics.
- Many factors account for how people feel about a sound, such as temporal variation and frequency density are important factors to impact people’s feelings about a sound. However, they are not designed to take these factors into consideration. In other words, these models could not provide objective measure about how a noise

abatement wall would really decrease/increase traffic noise impact to people.

Therefore, it is needed for the authors to investigate and develop objective and quantitative measures to evaluate noise abatement wall noise reduction effectiveness and acoustic properties using pre- and post-installation field noise data acquired at both the traditional noise and LOS wall sites. Moreover, the proposed measures are typically designed to evaluate the noise reduction effectiveness of the traditional concrete noise and LOS walls, and compare their noise reduction performances.

5.2 The Proposed Approaches

5.2.1 Design of Insertion Loss Spectrum Analysis

Traffic noise varies from time to time. Many factors can affect the characteristics of traffic noise: the current traffic patterns, the weather, the humidity, the road condition, etc. In order to measure how effective an in-situ sound barrier is, it is important to design a measure that would take the traffic dynamics into consideration and provide a reliable calculation. In this research, the authors proposed insertion loss spectrum density analysis to study noise abatement wall’s acoustic characteristics:

$$IS_i(f) = [S_{Aref}(f) + S_{edge}(f) - S_{Arec}(f)] - [S_{Bref}(f) - S_{Brec}(f)] \quad (5 - 5)$$

Where, $IS_i(f)$ is the insertion loss spectrum density at the 1/3 octave band centered at frequency f at the i^{th} receiver, $S_{Bref}(f)$ and $S_{Aref}(f)$ are the BEFORE and AFTER reference spectrum density at the 1/3 octave band centered at frequency f . $S_{edge}(f)$ is the edge diffraction correction factor spectrum density at the 1/3 octave band centered at frequency f . $S_{Brec}(f)$ and $S_{Arec}(f)$ are the BEFORE and AFTER adjusted source spectrum density at the 1/3 octave band centered at frequency f . In this way, the authors can analysis the noise reduction capability of the noise abatement wall in different frequency spectrum.

5.2.2 Design of Psychoacoustic Annoyance-based Measure

The insertion loss-based method is not designed to provide objective evaluation of how people would perceive traffic noise. In this project, the authors will calculate the normalized annoyance measure. The psychoacoustic elements of annoying sounds can be described by a combination of hearing sensations called psychoacoustic annoyance (46). Basically, the psychoacoustic annoyance depends on the loudness, roughness, sharpness, loudness, and fluctuation. The quantitative description of psychoacoustic annoyance is based on results of psychoacoustic experiments with modulated versus unmodulated narrowband and broadband

sounds of different spectral distribution. It is well-established and experimentally approved effective method in field to evaluate noise impact to human hearing perception. To provide a normalized noise impact evaluation after noise abatement walls, the authors proposed the normalized annoyance evaluation procedure.

Psychoacoustic annoyance: Psychoacoustic annoyance can quantitatively describe annoyance rating obtained in psychoacoustic experiments. Zwicker and Fastl used it to evaluate different sounds and their experiment results show that this method has good performance in predicting the annoyance of car sounds (46). Psychoacoustic Annoyance is calculated below:

$$PA = N_5 \left(1 + \sqrt{w_S^2 + w_{FR}^2} \right) \quad (5-6)$$

Where, N_5 is the 5th percentile loudness in sones (47), and

$$w_S = \left(\frac{S}{acum} - 1.75 \right) \cdot 0.25 \lg \left(\frac{N_5}{sone} + 10 \right) \quad (5-7)$$

if $S > 1.75$

$$w_{FR} = \frac{2.18}{(N_5/sone)^{0.4}} \left(1.4 \cdot \frac{F}{vacil} + 0.6 \cdot \frac{R}{asper} \right) \quad (5-8)$$

Where, S is sharpness in acum, F is fluctuation strength in vacil, and R is roughness in asper.

The detailed calculation of noise loudness, sharpness, roughness and fluctuation is discussed below.

Loudness: Loudness is an important sound quality metric; it is the perceived magnitude of a sound (47,48). The unit of dBA is commonly used to approximate the loudness and analyze traffic noise levels (49,50). A-weighting filter is based on the 40 Phon equal loudness curves. It is easy to implement, but it doesn't account for physiological phenomena such as frequency masking or the filter bank functioning of human ear. Chalupper and Fastl proposed a loudness model by processing the signal in a very comprehensive way.

Using the raw data rather than the 1/3 octave band, their proposed method can be more accurate and compensate for people for hearing loss.

Figure 5.1 shows the process of the loudness method. The critical band level will be obtained after the time signal is processed by high pass filter, critical band filter bank, and envelope extraction. In the next block transmission factor a_0 , the authors will get the main excitation of the original signal. The main loudness will be available after loudness transformation, which is the most crucial part. The relation between excitation and specific loudness is given by (50):

$$N'(z) = N_0 \left(\frac{E_{THQN}(z)}{s(z)E_0} \right)^\alpha \quad (5-9)$$

$$\left[\left(1 - s(z) + s(z) \frac{E(z)}{E_{THQN}(z)} \right)^\alpha - 1 \right] sone/Bark$$

Where, $E_{THQN}(z)$ is the excitation of normal hearing, N_0 is a constant for a loudness of 1 sone for a 1 kHz sinusoid with a level of 40 dB, and the exponent $\alpha = 0.23$ indicates that the specific loudness is related to the fourth root of intensity.

At the output of postmarking and upward spread summation blocks, the specific loudness pattern will be available. Finally, the authors will get the loudness of the original time signal after spectral summation and temporal integration blocks.

Sharpness: Sharpness is a sensation sound quality characteristic that is caused by high frequency sound, which is independent from total sound pressure level. The spectral envelope has little effect on sharpness; however the spectral content does greatly influence this calculation because this metric quantifies how much of a sound is made up of high frequency components. Sharpness is calculated by (50):

$$S = 0.11 \frac{\int_0^{24 \text{ Bark}} N' g(z) z dz}{\int_0^{24 \text{ Bark}} N' dz} \quad (5-10)$$

Where, N' is the specific loudness, $g(z)$ is a weighting factor, and the plot of $g(z)$ is shown in Figure 5.2. The

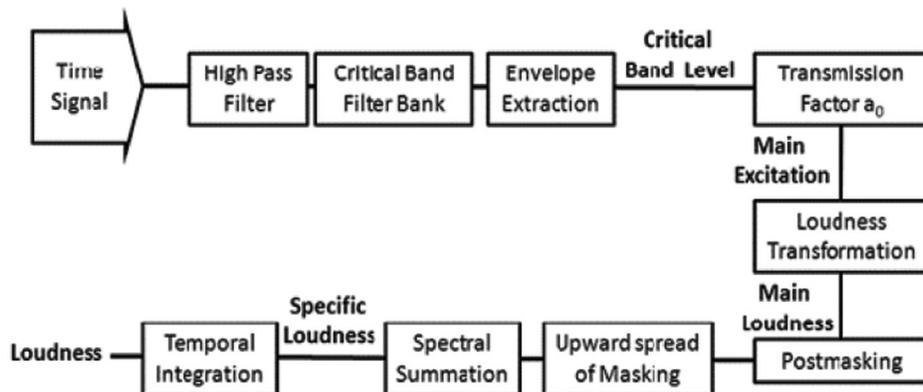


Figure 5.1 Chalupper and Fastl's loudness method (48).

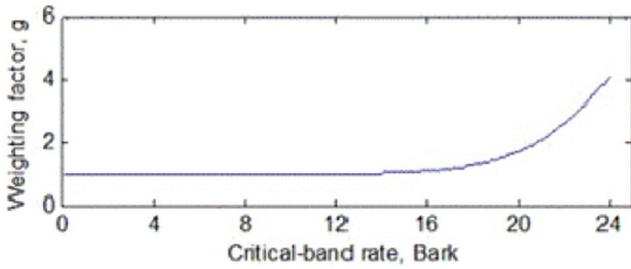


Figure 5.2 The plot of $g(z)$.

unit of sharpness is acum. The factor of 0.11 is to make a narrow-band noise centered at 1 kHz produce a sharpness of 1 acum.

Roughness: Roughness is a sensation caused by the fluctuation of sound in the 15 Hz to 300 Hz range. In this research, the authors used the roughness model which was proposed by Aures (51). This model is involved and requires a great deal of signal processing, and it has been implemented and optimized in by Daniels and Weber (52). Figure 5.3 shows the diagram of roughness model. Aures' model takes a time domain signal, using a Blackman window to frame the signal. A transformation of the frames to excitation patterns is the next step. Then, for each channel, the signal is

transformed into the frequency domain, and filtered in with a bandpass filter to isolate the frequencies contributing to roughness. The signal is divided by the DC to normalize it. Finally a correlation of the adjacent channels is taken to account for adjacent critical bands adding to the roughness. After that all the critical band channels are summed to make a total roughness.

Fluctuation strength: Fluctuation strength is a sensation similar to roughness which is caused by a variation of sound, but it measures the sensation of “slow moving” modulation in the range of variation at 20 Hz and below (51). Fluctuation strength and roughness have a similar description and overlapping range. The transition from roughness and fluctuation strength is not a black and white one; a sound can stimulate both of these sensations. The equation for fluctuation strength is:

$$F = \frac{0.008 \int_0^{24} (\Delta L / dB\text{Bark}) dz}{(f \text{ mod } / 4\text{Hz}) + (4\text{Hz} / f \text{ mod})} \text{ vacil} \quad (5 - 11)$$

Where, ΔL is the modulation depth of each critical band and f_{mod} is the modulation frequency. The unit for fluctuation strength is vacil, and 0.008 is used to normalize the measurement.

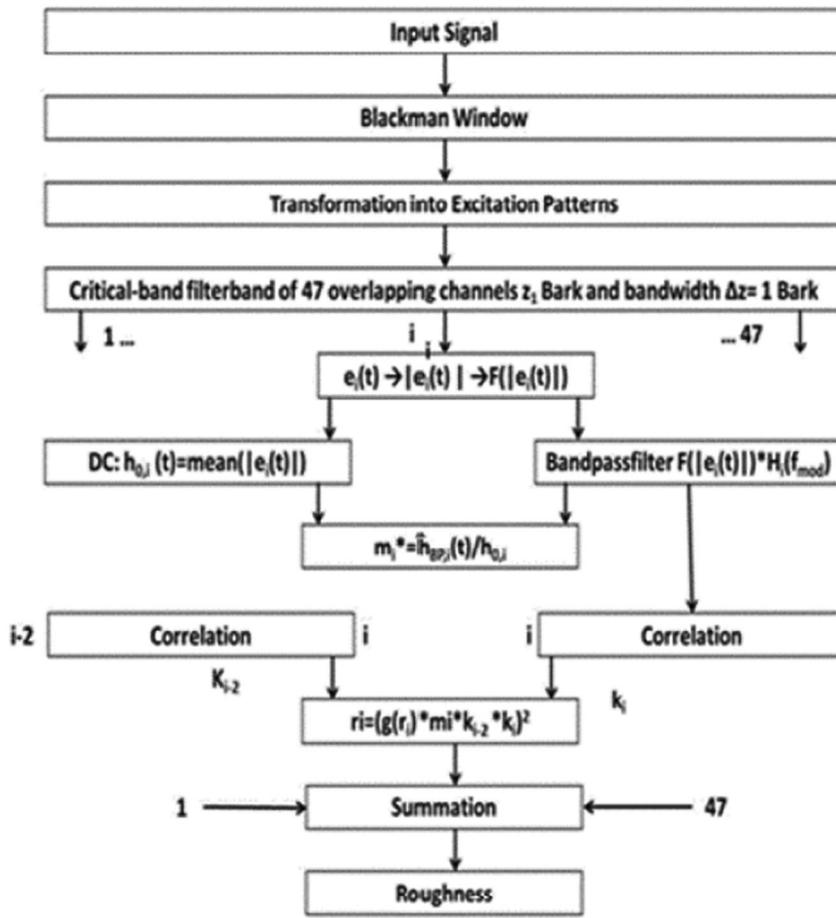


Figure 5.3 Diagram of roughness model (52).

5.2.3 Normalized Psychoacoustic Annoyance Approach

To normalize the variance of traffic noise at different measurement time and study the effectiveness of the noise abatement wall at different location with different geographic environment, the authors designed the normalized psychoacoustic annoyance measurement approach. Figure 5.4 shows the process of our approach.

For each location X, the data is first registered with that in the reference location. Then the authors calculate loudness, sharpness, fluctuation, and roughness for data from both location X (L_X, S_X, F_X , and R_X) and reference location ($L_{iRef}, S_{iRef}, F_{iRef}$, and R_{iRef}). Based on these psychoacoustic features, obtain the annoyance for location X (PA_X) and reference location (PA_{iRef}). In order to mitigate the variation of highway traffic, the authors calculate the normalized annoyance approach. From the annoyance in location X and reference location, we could get the normalized annoyance for location X at time i by:

$$NormPA_X^i = \frac{PA_X^i}{PA_{iRef}^i} \quad (5 - 12)$$

Where, PA_X^i is the annoyance for location X, PA_{iRef}^i is the annoyance for reference location in i^{th} time, and T is the total measure time. Based on the normalized annoyance, the authors can obtain the normalized annoyance distribution for location X:

$$P(NormPA_X = k) = \frac{N(NormPA_X = k)}{N_X} \quad (5 - 13)$$

Where, N_X represents the total number of points measured, and $NormPA_X = k$ denotes the number of points which have normalized annoyance = k .

Presented in Figures 5.5 and 5.6 is an example of our proposed approach to calculate the normalized annoyance distribution for location X. Based on the registered data, the annoyances in location X (Figure 5.5) are first calculated. Similarly, the authors calculated annoyances in reference location. Second, the normalized annoyance for location X is obtained by these two annoyances. Finally, the authors will get normalized annoyance distribution for location X. As shown in Figure 5.6 is an

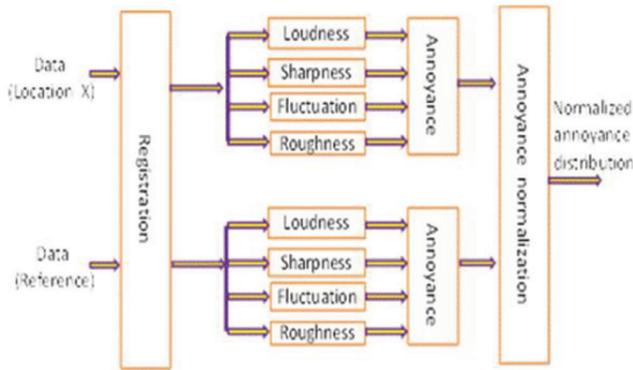


Figure 5.4 The process of the proposed approach.

example annoyance distribution calculation at Location X. After all annoyances are determined, the authors are able to compare the normalized annoyance distribution at Location X pre- and post-installation to evaluate the annoyance reduction capability due to a specific noise wall.

To provide more objective and equalized dBA analysis, the authors performed series of field tests and theoretical analysis in this project. Figure 5.7 shows the relationship between equalized insertion loss (dBA) and annoyance reduction.

5.3 Pre- and Post-Installation Field Noise Data Collection

Since March 2011, the authors have worked on field data collection. In this project, INDOT has built four types of noise walls (see Chapter 3): Durisol precast concrete (NRC = 0.85), Noise D-Fence (absorptive, NRC = 0.75), Sanders precast (absorptive, NRC = 0.75), and AAC (reflective, NRC = 0) noise walls along interstate I-465 (nearby the intersection between I-465 and Keystone Ave.). Figure 5.8 shows the locations of the four noise walls. On the north side of I-465, Durisol precast concrete noise wall was built in NSA2 and NSA3. On the south side of I-465, three kinds of LOS noise walls, including AAC (reflective), Noise D-Fence (absorptive), and Sanders Precast (absorptive) noise walls were built in NSA1. Table 5.1 summarizes the dimension and sound property information of the noise abatement walls. The detailed information on these noise walls can be found in Chapter 3. The noise walls were built only on a single side of the highway while the other side is basically an open area. In this way, the authors can study and evaluate the impact of a single noise abatement wall.

To accurately evaluate the sound barrier effect, the authors made an effort to mitigate the impact of highway traffic variations. The authors acquired the reference data and observer data synchronously. The receivers (microphones) were positioned in different locations. One was positioned to measure the source noise energy as the reference point. Others were positioned outside of highway (the other side of sound wall) to measure the noise energy and evaluate how much noise reduction was achieved by the sound wall. The number of receivers to be used was determined by site situations. For dense residential places, more receivers were necessary to provide more coverage and higher resolution of the measurement. Also, ANSI Type I sound level meters (SLMs) were used to record the traffic noise. For this experiment Larson Davis 831 with an inch microphone was used. The SLMs were calibrated with ANSI Type I calibrator before and after an experiment to verify the accuracy of the instruments. The sample rate used was 48 kHz, allowing for analysis up to the highest frequency that humans can hear.

For the noise measurements behind the wall, camera style tripods were used to hold the SLMs. For the reference SLM a system was devised to hold the SLM

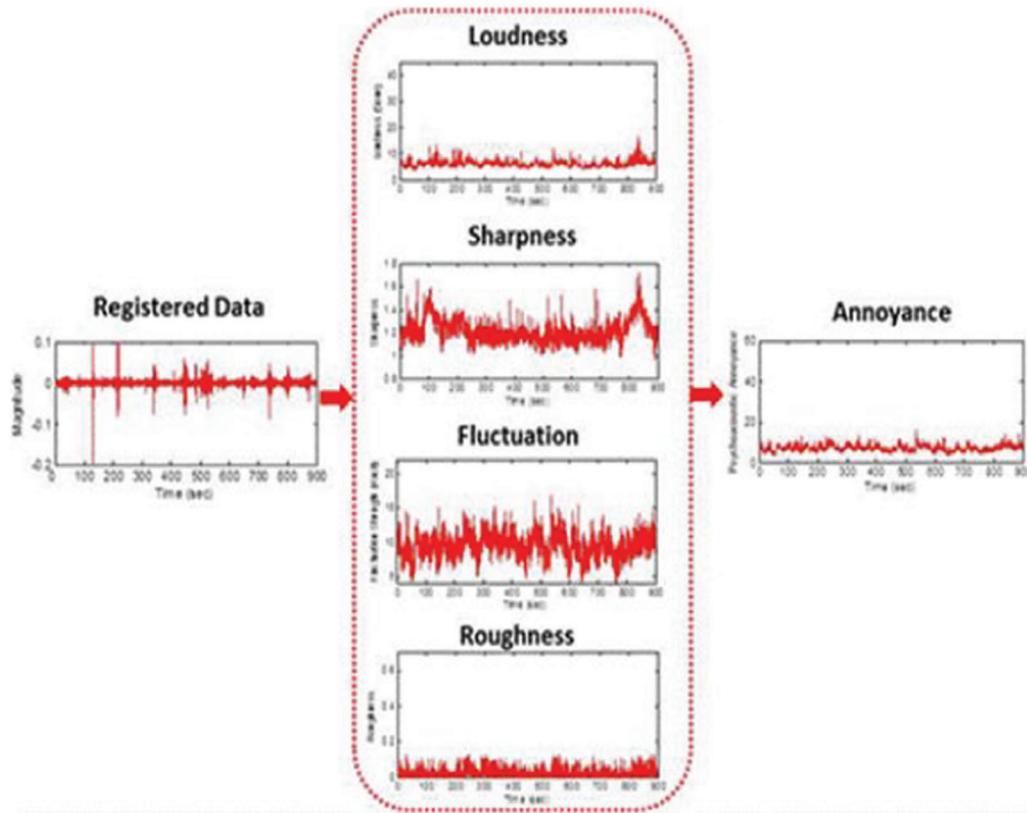


Figure 5.5 Proposed approach: Annoyance calculation in Location X.

higher than the wall. A handheld GPS unit was used to record the location of the each SLM. Digital images of all the locations were taken as well to insure that the exact locations could be repeated on future visits. To synchronize the SLMs the internal clocks were used. During data collection process, an operator manually recorded the incidence time, pattern, duration, and affected data collection station number(s). If the impact

time period was longer than 30 seconds, the authors would add an additional recording time based on the length of the incidence time. After data collection, the authors first checked the collected data at the incidence period. Since the authors recorded raw data and sound wave, the authors listened to the data segment to verify the data. After confirmation, the impacted segments was flagged and removed for further processing.

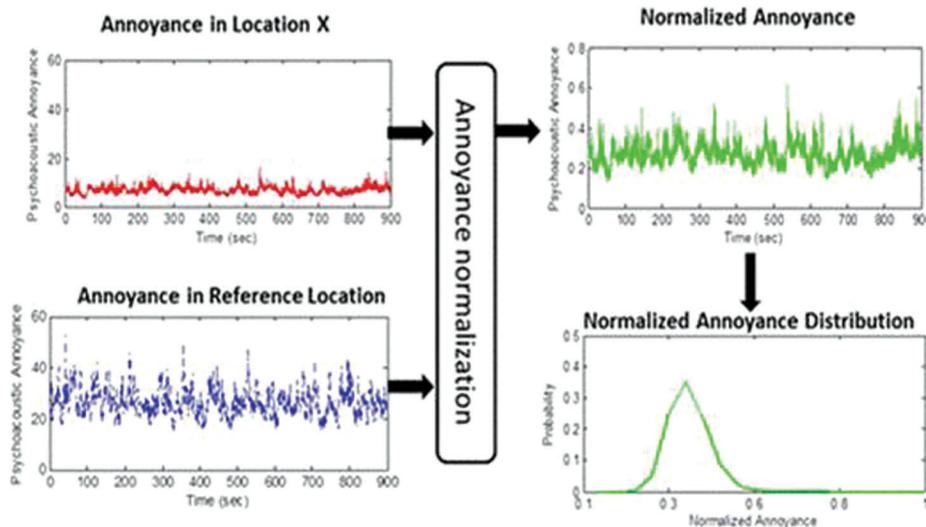


Figure 5.6 Proposed approach: Normalized annoyance distribution.

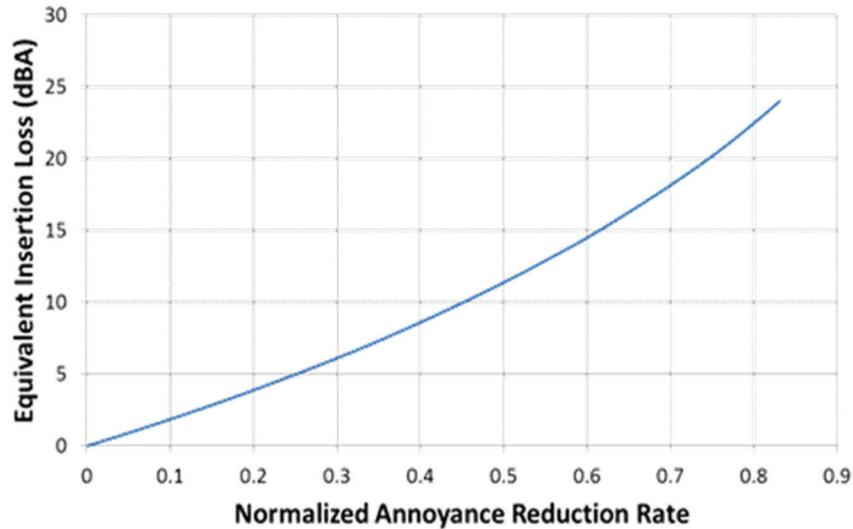


Figure 5.7 Normalized annoyance reduction rate versus equivalent insertion loss.



Figure 5.8 Geographical locations of study sites.

5.4 Spectrum Density Analysis of Insertion Loss and Psychoacoustic Annoyance Analysis of Effectiveness

5.4.1 Durisol Precast Concrete Wall

Figure 5.9 shows the locations in the north of I-465 and Guilford Avenue, where is built with Durisol precast concrete sound walls of 10–23 ft. tall. The authors measured noise data at 11 locations including

AR (reference location), A1, A2, A3, A4, A5, A6, A7, A8, A9, and A10 before and after building the concrete sound wall with a height of 22 ft.

Figure 5.10 shows the insertion loss spectrum density at these 10 locations, including A1 to A10 as shown in Figure 5.9. It is shown that the noise levels after the installation of the Durisol concrete sound wall has decreased significantly at all 10 locations compared to those before the construction of the noise wall. It can be

TABLE 5.1
Noise Walls Dimensions and Sound Properties

Test Site	Type of Barrier Panel	Dimension of Barrier Panel (inch)			NRC
		Length	Height	Thickness	
NSA1	AAC	800	10–12	7.87	0
	Noise D-Fence	694	10	4.0	0.75
	Sanders Precast	674	10	7.0	0.75
NSA2 & NSA3	Durisol Precast	5,204	10–23	8.0	0.80



Figure 5.9 Noise measuring locations at Durisol precast noise walls (NSA3).

concluded that the Durisol precast concrete wall at a normal height (22 ft) can reduce noise impact across different sound frequencies (from low frequency to high frequencies).

Figure 5.11 shows the distributions of the normalized annoyance on both sides of the Durisol precast noise wall. It is shown that the normalized annoyance on the residence side of the Durisol concrete noise wall has a significant reduction compared to that on the roadway side of the Durisol concrete noise wall. The average of normalized annoyance for all locations on the roadway side of the Durisol concrete noise wall is around 0.9. And the average of normalized annoyance for all locations on the residence side of the Durisol concrete noise wall decreases to be around 0.2.

Table 5.2 shows the average normalized annoyance reduction and the effective intensity reduction (equiva-

lent insertion loss) at each location. The authors found that all of the locations have significant normalized annoyance reduction of traffic noise. In addition, the equivalent insertion loss is greater than 18 dBA. The Durisol concrete noise wall can dramatically reduce the noise levels.

Figure 5.12 shows the locations in the north of I-465 and 939 E 101st Street with 10 ft. high wall. The authors measured noise data at 6 locations including BR (reference location), B1, B2, B3, B4 and B5 after the construction of the Durisol precast concrete sound wall. Also, the authors used the data from location A1, A4, A5 and A7 to estimate the pre-construction situation since they have similar geometric characteristics. It is shown that the noise levels after the construction of the noise wall has experienced a dramatic reduction compared to those before the construction of the noise

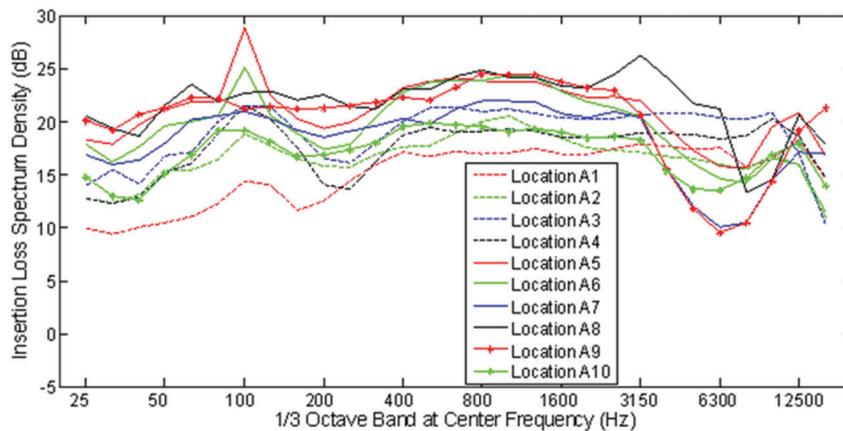


Figure 5.10 Insertion loss spectrum density (22 ft. high wall).

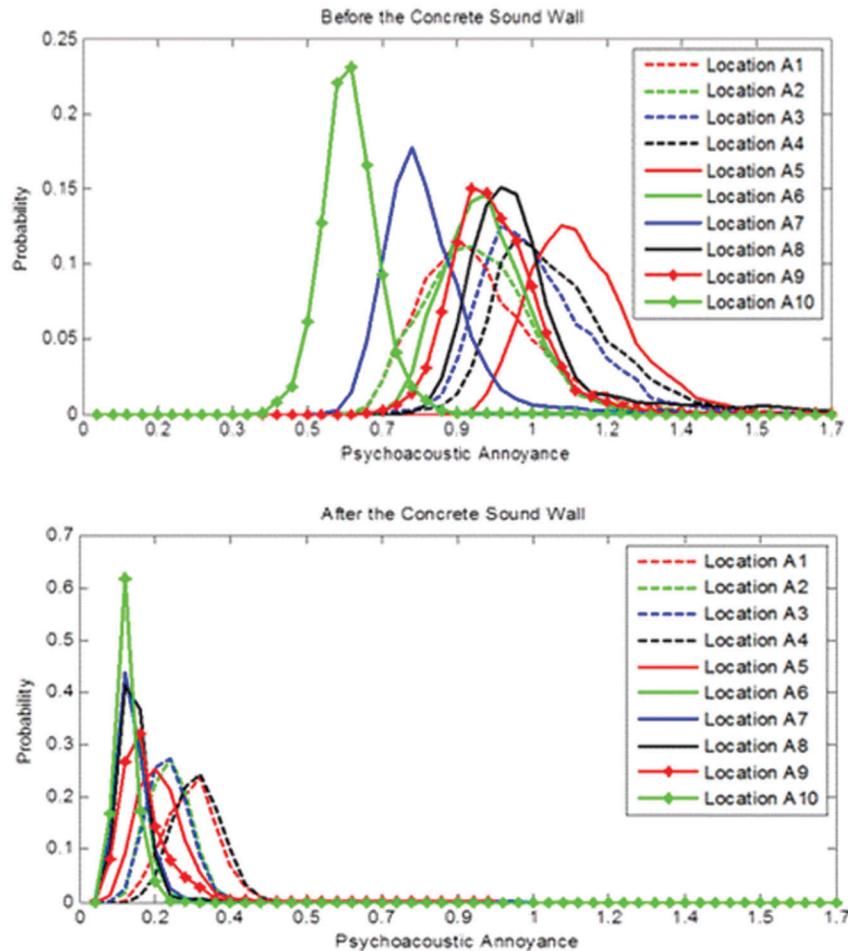


Figure 5.11 Probability distributions of normalized noise annoyances (22 ft. high wall).

wall in the frequency bands from 11 Hz to 3548 Hz. Its effectiveness reduced in frequency bands from 3548 Hz to 10000 Hz.

Figure 5.13 shows the probability distributions of the normalized annoyance before and after the construction of the 10 ft. high Durisol precast concrete wall. The average of normalized annoyance for all locations before the construction of the 10 ft. high Durisol precast

concrete wall is around 0.9 and the average of normalized annoyance for all locations after the construction of the 10 ft. high Durisol precast concrete wall decreases to around 0.3, which is a dramatic decrease since the normalized annoyance ranges between 0 and 1.

Table 5.3 shows the average annoyance reduction and the effective intensity reduction (equivalent insertion loss) for each location. It was found that the noise

TABLE 5.2
Average Annoyance and Effective Intensity Reductions (22 ft. High Wall)

Location	Average Annoyance Reduction	Effective Intensity Reduction (Equal Level)
A1	68.8%	18–19 dBA
A2	72.7%	19–20 dBA
A3	77.6%	20–21 dBA
A4	71.3%	18–19 dBA
A5	72.3%	19–20 dBA
A6	80.6%	22–23 dBA
A7	81.2%	23–24 dBA
A8	84.2%	24–25 dBA
A9	80.0%	22–23 dBA
A10	82.7%	23–34 dBA

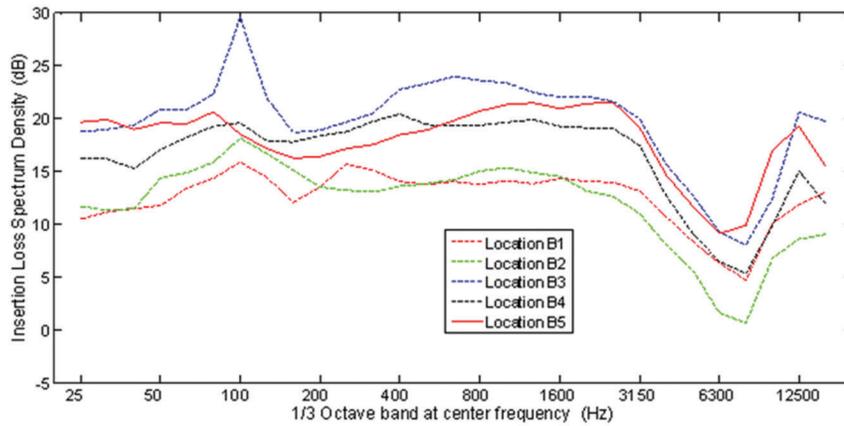


Figure 5.12 Insertion loss spectrum density (10 ft. high wall).

impact reduction capability of the 10 ft. high concrete wall is not as good as that of the 22 ft. high Durisol noise wall. The noise reduction capability of 10 ft high concrete wall at the location closer to the wall is (14~15 dBA in location B1 and B2) is much lower than that of

the 22 ft. high Durisol noise wall. However, the noise reduction capability of 10 ft high Durisol noise wall at further locations (20~21 dBA in average in location B3, B4, and B5) is a little lower than that of the 22 ft. high Durisol noise wall.

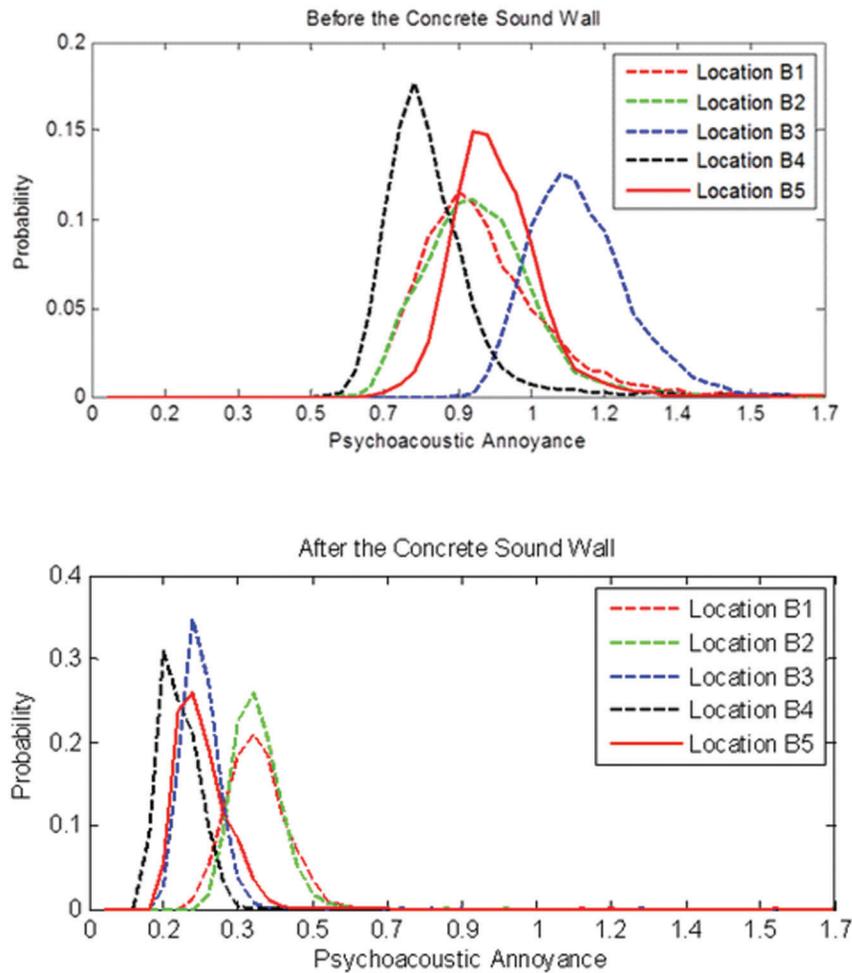


Figure 5.13 Probability distribution of normalized annoyance (10 ft. high wall).

TABLE 5.3
Average Annoyance and Effective Intensity Reductions (10 ft. High Wall)

Location	Average Annoyance Reduction	Effective Intensity Reduction (Equal Level)
B1	59.1%	14–15 dBA
B2	58.8%	14–15 dBA
B3	78.7%	21–22 dBA
B4	75.6%	20–12 dBA
B5	73.8%	19–20 dBA

5.4.2 LOS Walls

Figure 5.14 shows the noise test locations in the south of I-465 and keystone Avenue where with the three LOS walls, including ACC, Noise D-Fence and Sander precast walls, are placed. In order to evaluate the effectiveness of these three LOS walls, the authors measured noise data at locations C1, C2, C3, D1, D2, D3, E1, E2, E3, F1, F2 and F3 in addition to three reference locations. Because these three kinds of LOS walls are placed close to one another, acoustic signals acquired in locations far from a LOS wall may be impact by the other LOS walls. Therefore, the authors only acquired data from those locations close to the walls to evaluate the effectiveness of the three different LOS walls. Locations As shown in Figure 5.14, including C1, C2, and C3, are behind the AAC wall. Locations D1, D2, and D3 are behind the connection of the AAC and Noise D-Fence walls. Locations E1, E2, and E3 are behind the Noise D-Fence wall. Locations F1, F2, and F3 are behind the Sander precast wall. Presented in Figures 5.15, 5.16 and 5.17 are the results of the normalized insertion loss spectrum analysis conducted on the three LOS walls, respectively.

Presented in Figure 5.15(a) are the calculated insertion loss spectrum densities at Locations C1, C2, and C3, respectively, which are behind the AAC wall. It can be observed that the AAC wall has resulted in a noise reduction at C1, which is located just 5 feet behind the AAC wall. However, at locations C2 and C3, the AAC wall demonstrated some noise reduction capability in

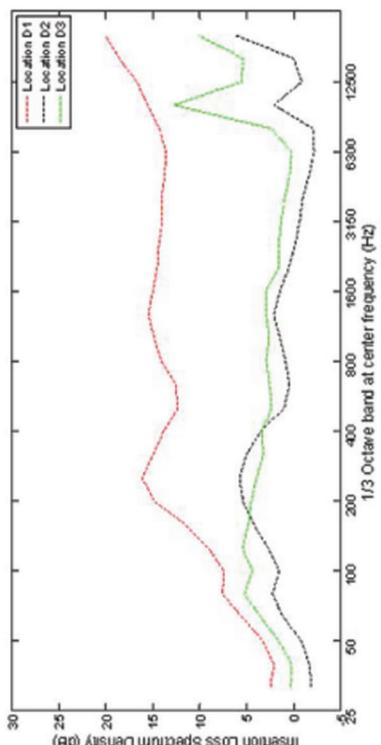
frequencies over 8000 Hz. In the middle range of frequency, the AAC wall demonstrated little noise reduction capability. In the low frequency bands (lower than 200 Hz), the AAC wall might result in a noise increase, i.e., the insertion loss becomes negative. This can be seen from the curves at C2 and C3 in Figure 5.15(a).

Figure 5.15(b) shows the calculated insertion loss spectrum densities at Locations D1, D2, and D3, respectively, which are behind the connection of the AAC and Noise D-Fence walls. It is demonstrated that a noise reduction occurred at Location D1, which is located just 5 feet behind the connection. At Locations D2, there is only a little insertion loss in frequency bands of 178 Hz~2818 Hz and in frequencies greater than 8913 Hz. However, in both frequency bands lower than 178 Hz and the frequency bands ranging between 2818 Hz and 8913 Hz, there is an increase in noise level, i.e., negative insertion loss. At locations D3, there is some insertion loss in high frequency bands (frequency greater than 8913 Hz) but there is a little insertion loss in low and middle frequency bands.

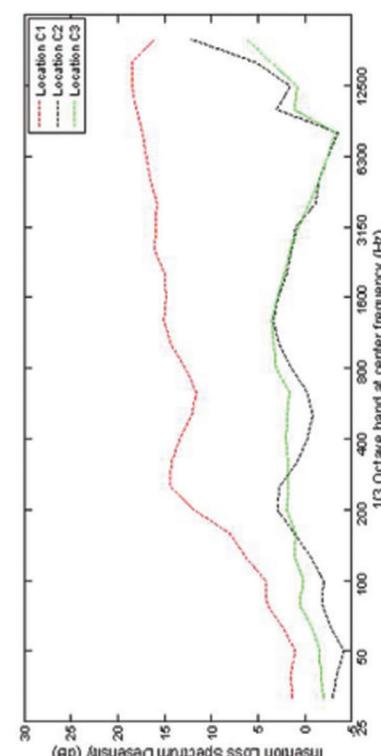
Figure 5.15(c) shows the calculated insertion loss spectrum densities at Locations E1, E2, and E3, respectively, which are behind the Noise D-Fence wall. It is demonstrated that noise reductions occurred at Locations E1 (about 5 feet behind the wall) and E3. At Location E1, there an insertion loss more than 10 dB occurred in frequency bands greater than 178 Hz. At Locations E2, in frequency bands between 178 Hz and



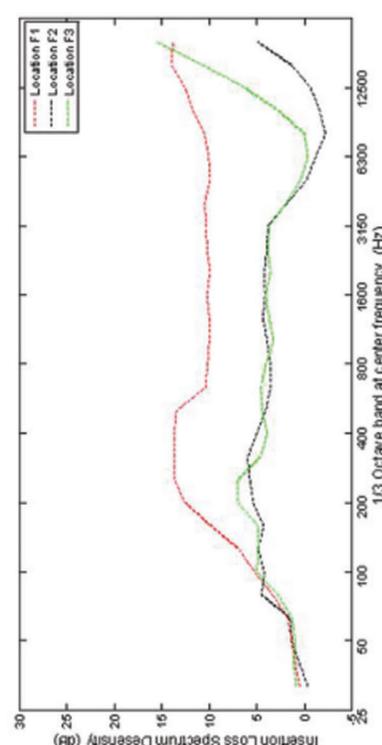
Figure 5.14 Noise measuring locations at LOS walls (NSA1).



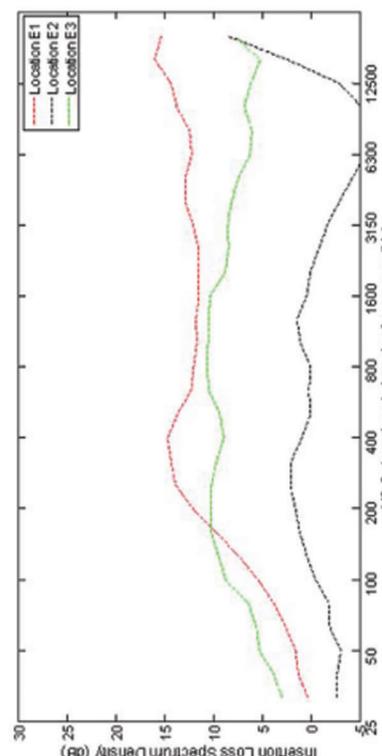
(a) AAC wall at Location C



(b) AAC wall at Location D



(c) Noise D-Fence wall at Location E



(d) Sanders Precast wall at Location F

Figure 5.15 Insertion loss spectrum densities at different locations for LOS walls.

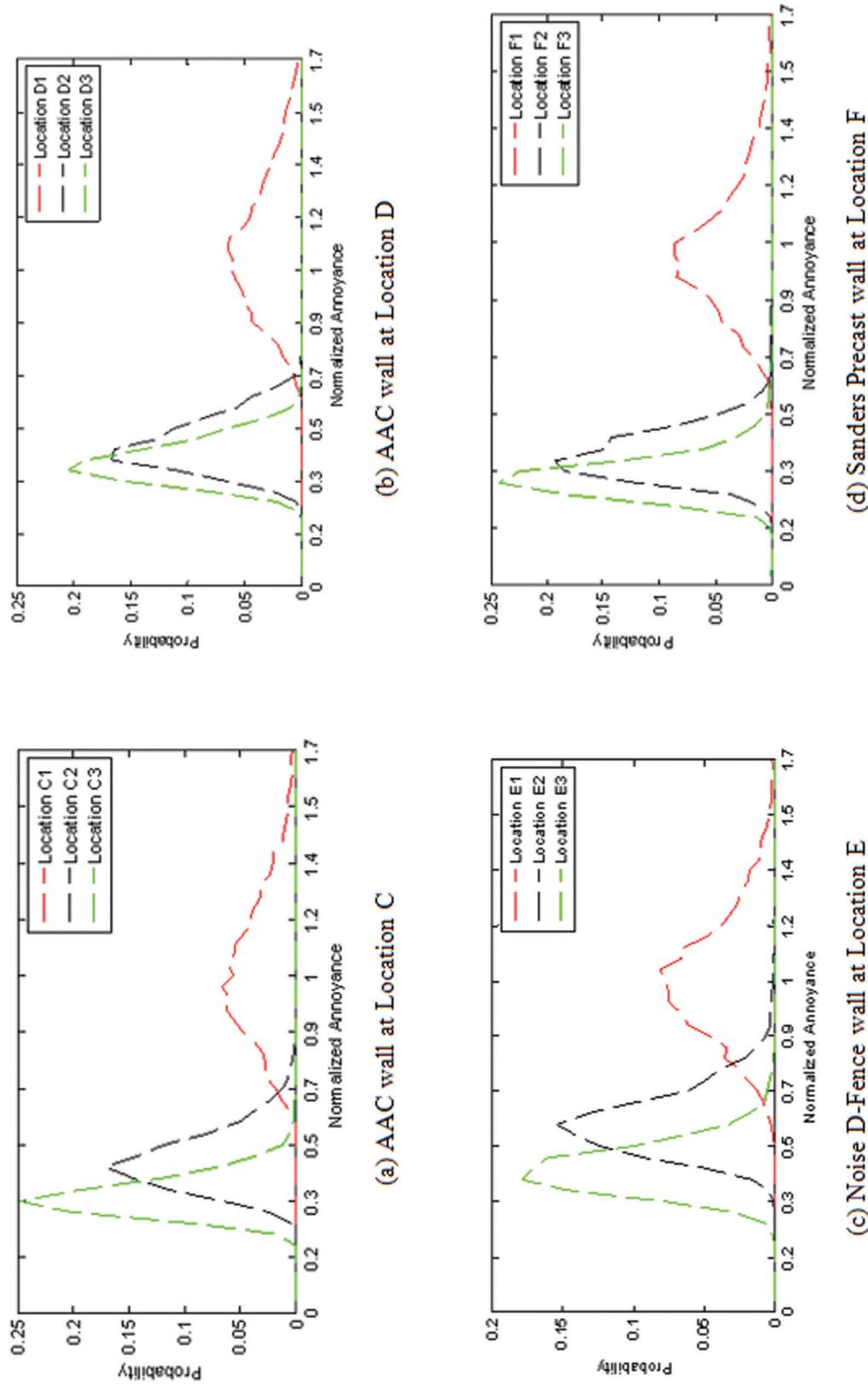
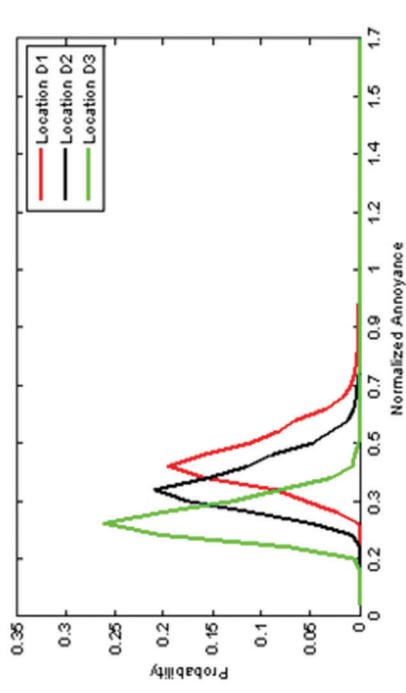
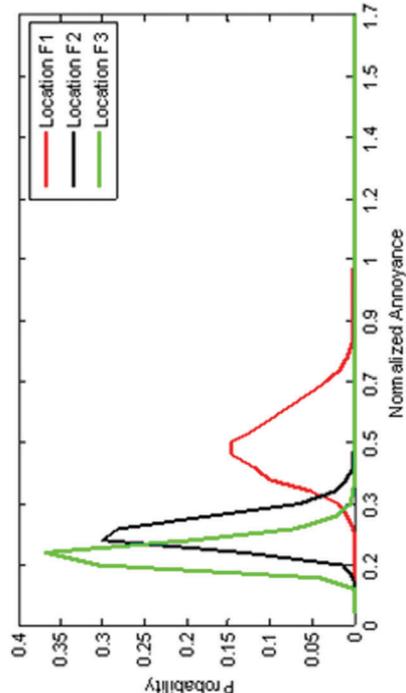


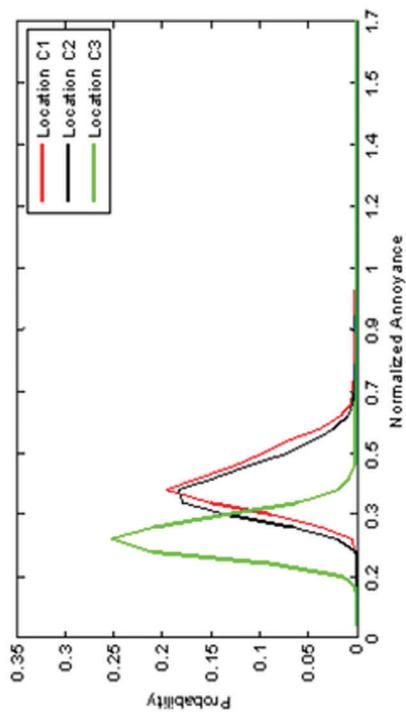
Figure 5.16 Probability distributions of the normalized annoyance before LOS wall construction.



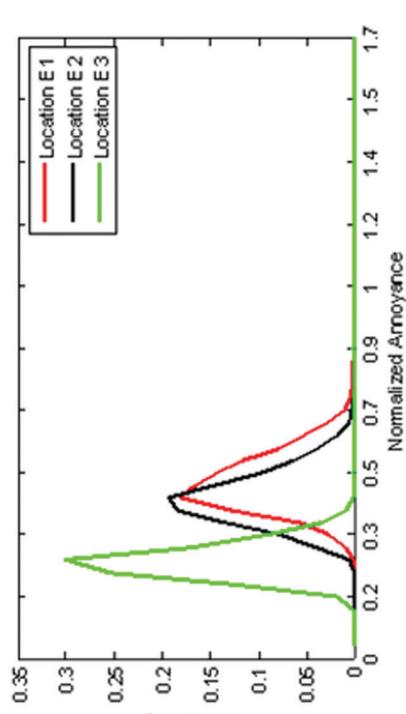
(b) AAC wall at Location D



(d) Sanders Precast wall at Location F



(a) AAC wall at Location C



(c) Noise D-Fence wall at Location E

Figure 5.17 Probability distributions of the normalized annoyance after LOS wall construction.

5623 Hz, the insertion loss is about 10 dB. The insertion loss gradually reduced when frequency decreases below 200 Hz. At locations E2, there is almost no insertion loss or even negative insertion loss in frequency bands below 14130 Hz. There is some insertion loss in high frequency bands (frequency greater than 14130 Hz).

Figure 5.15 (d) shows the calculated insertion loss spectrum densities at Locations F1, F2, and F3, respectively, which are behind the Sander precast wall. It is shown that there is about a 10 dB noise level reduction at Location F1 (about 5 feet behind the wall) in frequency bands greater than 178 Hz. At Locations F2 and F3, there is about a 5 dB noise level reduction in frequency bands ranging from 89.1 Hz to 3548 Hz. Then noise level reduction is gradually reduced in frequency bands from 3548 Hz to 8913 Hz. After 8913 Hz, the noise level reduction is gradually increased.

Presented in Figures 5.16 and 5.17 are the normalized annoyance distributions before and after the construction of the LOS walls, respectively. As shown in Figure 5.16, the normalized pre-construction annoyance distributions for the three different LOS walls follow a similar trend. First, all distribution curves are approximately bell-shaped and symmetric, regardless of the type of wall and test location. As the test location gets closer to the LOS wall, the distribution curve shifts to the right and becomes flatter and more spread-out, resulting in a greater mean annoyance. It can also be observed from the curves in Figures 5.16 and 5.17, the annoyance distribution curves have shifted to the left and become narrow after the construction of the LOS walls. This simply indicates that after the construction of the LOS walls, the mean annoyance has decreased and become more concentrated.

Table 5.4 shows the average normalized annoyance reduction and the equivalent insertion loss at each test location behind the LOS walls. It is shown that LOS walls can provide some reduction of noise annoyance impact. The closest houses to the LOS walls received lower noise impact reduction. Among these three kinds of LOS wall, D-Fence wall and Sander's precast wall performed better than AAC wall.

TABLE 5.4
Average Annoyance and Effective Intensity Reductions (LOS Walls)

Location	Average Annoyance Reduction	Effective Intensity Reduction (Equal Level)
C1	59.5%	14-15 dBA
C2	10.6%	2-3 dBA
C3	20.9%	6-7 dBA
D1	58.9%	14-15 dBA
D2	15.2%	2-3 dBA
D3	29.5%	5-6 dBA
E1	53.8%	12-13 dBA
E2	25.9%	5-6 dBA
E3	39.6%	9-10 dBA
F1	49.6%	11-12 dBA
F2	33.5%	6-7 dBA
F3	38.9%	8-9 dBA

5.4.3 Noise Reduction Capability Comparisons among Conventional Noise and LOS Walls

To compare noise reduction effectiveness of these four kinds of walls, the authors used the measured average insertion loss spectrum density, and average normalized annoyance reduction rate. While the geographic characteristics and distances to the walls may vary in these locations, the average could provide us some information about the noise reduction effectiveness of these noise walls based on sound pressure level. Presented in Figure 5.18 are the plots of insertion loss spectrum densities of the four different walls, including Durisol precast concrete wall (conventional), AAC wall, Noise D-Fence wall, and Sanders Precast wall.

For concrete wall, the authors compared normal height concrete wall (called "concrete wall" in the figure) and shorter concrete wall. For the 22 ft. high Durisol precast wall, the average insertion loss spectrum density was calculated by averaging the insertion loss spectrum densities from Locations A1 to A10. For the 10 ft. high Durisol precast wall, the average insertion loss spectrum density was obtained by averaging the insertion loss spectrum densities from Locations B1 to B5. For each LOS wall, the average insertion loss spectrum density was calculated by averaging the insertion loss spectrum densities measured at the three locations, i.e., Locations C1 to C3 for AAC wall, Locations E1 to E3 for Noise D-Fence wall, and Locations F1 to F3 for Sander precast wall. The data from D1 to D3 was not used because they are located behind the connection of AAC and Noise D-Fence walls.

It can be observed that from Figure 5.18, the Durisol precast concrete wall can dramatically reduce noise impact across different acoustic spectrums (from low to high frequencies). The noise reduction capability of the Durisol precast wall varies with the height of the wall. The noise reduction for a shorter Durisol precast wall will be less effective; particularly in frequency bands between 2828 Hz to 14130 Hz. The noise reduction for LOS walls is less effective than that for Durisol precast wall. In particular, the noise reductions for LOS walls are not very effective in low frequency bands (lower than 178 Hz). In some very low frequency bands (less than 44.7 Hz), AAC wall may increase the noise level.

Table 5.5 summarizes the average normalized annoyance reductions and equivalent insertion losses by different noise walls. For each type of the noise wall, the authors used the similar locations to average the results as the authors did in Figure 5.18. It is demonstrated that overall, the Durisol precast concrete wall performs better than these LOS walls in noise reduction. The height of the Durisol precast wall could affect its noise reduction capability. The LOS walls can also reduce the noise impact. However, their noise reduction capabilities are not as good as the Durisol precast wall in terms of both intensity and annoyance reductions. For the three LOS walls, Sanders precast

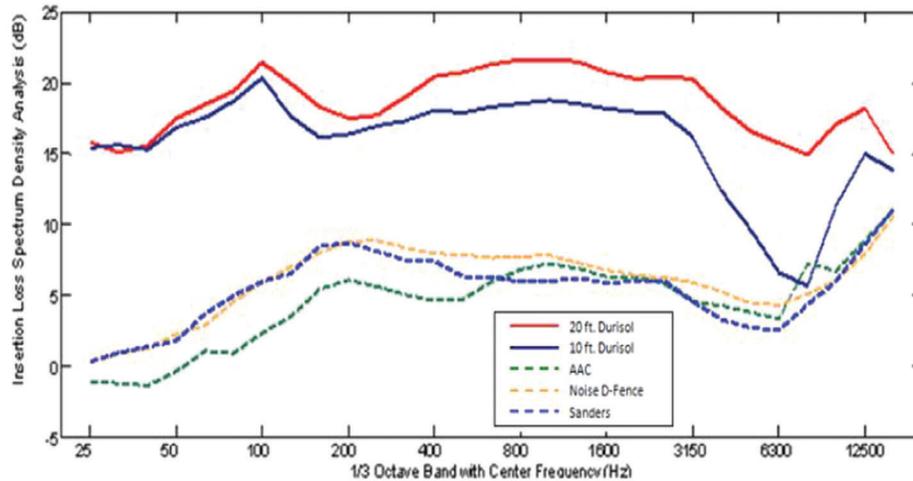


Figure 5.18 Insertion loss spectrum densities of different walls.

TABLE 5.5
Average Annoyance and Effective Intensity Reductions by Different Walls

Location	Average Annoyance Reduction	Effective Intensity Reduction (Equal Level)
20 ft. High Durisol Wall	77.2%	20–21 dBA
10 ft. High Durisol Wall	69.2%	18–19 dBA
AAC Wall	30.3%	5–6 dBA
Noise D-Fence Wall	38.8%	8–9 dBA
Sanders Precast Wall	40.7%	10–11 dBA

wall is more effective than the Noise D-Fence and AAC walls in terms of noise reduction.

6. PREDICTION AND ANALYSIS OF TRAFFIC NOISE OVER DESIGN YEAR

6.1 Construction of Noise Prediction Models Using FHWA TNM 2.5

6.1.1 FHWA Traffic Noise Model TNM 2.5

FHWA Traffic Noise Model (TNM[®]) is a state-of-the-art analytical computer program that was originally developed and validated through the U.S. Department of Transportation’s John A. Volpe National Transportation Systems Center, Acoustics Facility. The FHWA TNM 1.0 was first released in March 1998. Afterwards, FHWA TNM has been upgraded several times with advance in computer hardware and highway noise modeling software. The current TNM software is FHWA TNM 2.5, which released in April 2004. Compared to the previous versions, FHWA TNM 2.5 adds major improvements in the acoustics (53). Among these improvements, FHWA TNM 2.5 made an improvement the implementation of the vehicle emission level database, a more comprehensive methodology was applied in correcting the measured emission levels back to the source. It also improves accuracy of modeling traffic noise with a

scientifically founded and experimentally calibrated acoustic computation methodology, particularly the diffraction algorithm.

As with the previous versions, FHWA TNM 2.5 provides a wide range of functions. It models five standard types of vehicles (automobiles, medium trucks, heavy trucks, buses, and motorcycles) and user-defined vehicles. It also models traffic flow as either constant-flow or interrupted-flow based on new field measurements. FHWA TNM 2.5 considers the effects of pavement surface type, roadway grade, buildings, and dense vegetation. Sound levels are computed as one-third octave band sound levels so as to provide detailed noise structure, better characterize human-ear perception and enhance repeatability. FHWA TNM 2.5 can facilitate users in noise barrier optimization design in compliance with the FHWA noise regulations, i.e., 23 CFR Part 772, and perform multiple diffraction analysis and parallel barrier analysis. The distribution analysis provides sound level distributions, barrier insertion loss distributions, and sound-level difference distributions.

In addition, FHWA TNM 2.5 enhances software usability with the advance of computer hardware technologies. It adds error messages with a new pop-up warning box or a dialog pop-up box when an unexpected condition occurs, particularly each time an input error arises. FHWA 2.5 contains the common

input features of the previous versions. The Graphical User Interface (GUI) has been fine tuned to applications easier to use. Users can import Stamina 2.0/Optima files and roadway design files saved in a Computer-aided Design (CAD), Drawing Exchange Format or Drawing Interchange Format (DXF) format. Color graphics makes it easier and more appealing for visual inspection and comparison of sound level, noise distributions, barrier insertion loss, and sound-level differences.

6.1.2 Creation of DXF Input File

To perform traffic noise prediction in the design year, i.e., 20 years in the future for this study, the three noise sensitive areas defined in Chapters 3 and 4, including NSA1, NSA2 and NSA3, were utilized. It should be reiterated that the selection of the locations of noise monitoring receivers was made by taking into consideration the noise levels at possible impacted and benefited residential homes in the three NSA areas, effects of different noise walls, effects of varying ground conditions, topography and elevation, and the concerns raised by the residents, in particular those in NSA1 and NSA3. The detailed locations and addresses with respect to the noise monitoring locations can also be found in Chapters 3 and 4.

To perform traffic noise analysis using FHWA TNM 2.5, the key input is the so-called TNM. DXF input file. A DXF file is an AutoCAD data file format. In FHWA

TNM 2.5, a DXF input file is typically intended to provide a reasonable representation of the natural and man-made objects, such as roadways, building rows, noise walls, ground type, and noise receivers. In reality, there was no information on the coordinates of some natural and man-made objects in the design drawings. Also, there were some differences between the design and the completed project. In order to create a DXF file containing necessary inputs, the DXF input file was developed on the basis of the design drawings such as Noise Abatement Plans and Construction Details, Google map, and measured coordinates of building rows and tree rows using the AutoCAD software as follows:

1. Creation of CAD Base Map

- Select the area of interest in Google Map, edit the map by adding features, and save it as a customized image jpg file.
- Import the image jpg file to AutoCAD using the Imageattach command (Figure 6.1)
- Calibrate the imported image in AutoCAD by comparing the distances measured in Google Map and in AutoCAD using the Dist Command. Adjust the map size in AutoCAD until the error of distance becomes tolerant, i.e., within $\pm 1\%$ defined by the authors.

2. Creation of CAD DXF Input File

- Import the design drawings containing the horizontal alignment of roadway and noise barriers into AutoCAD.

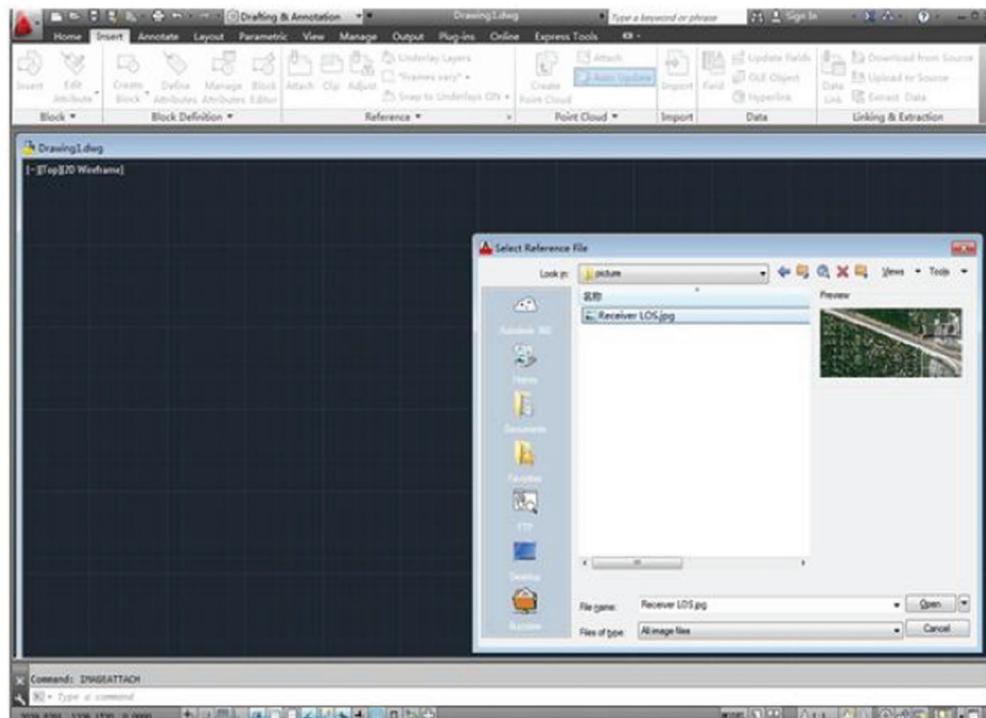


Figure 6.1 Screenshot of importing Google Map.

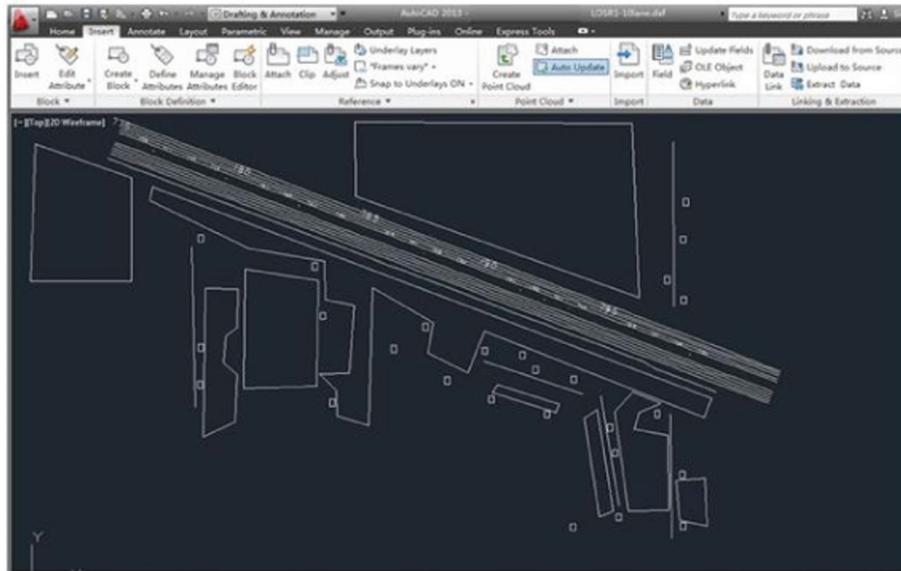


Figure 6.2 Screenshot of measuring distance using Dist Command.

- Copy and paste the road alignment from the design drawings onto the CAD Base Map in the AutoCAD Drafting and Annotation Interface.
- Add lane lines, noise wall lines, tree zones, building rows, ground zones, and noise receivers in AutoCAD plot model window, and then save it as a CAD DXF file (see Figure 6.2).

The drawing explanation is presented in Table 6.1. Notice that there is no simple, unique and direct method to create a DXF input file for running TNM analysis. It takes time for users to practice until you find something workable. For this study, the lane lines and noise wall lines were drawn in terms of different road sections between two consecutive stations for the convenience of analysis and execution. The positions of lane lines and noise wall lines were determined in terms of reference positions, such as roadway centerline or outside edge of roadway, and the distance between different objects. The lane width was adjusted to 12.1 ft to provide 0.1 ft roadway overlap to avoid exactly matching the edges of the roadways. Figure 6.3 shows the drawings created for NSA1, NSA2, and NSA3 in TNM 2.5, respectively. There are a total of 10 traffic lanes in both directions in the project area.

TABLE 6.1
Drawing Explanation

Symbol	Object
	Roadway
	Noise Wall
	Building Row
	Receiver
	Tree Zone
	Distribution Zone

6.1.3 Determination of TNM Inputs

The elevations of tree zones, building rows and noise walls were determined using the technique of trigonometric leveling. Presented in Figure 6.4 are three photos showing the leveling team at work to measure the elevations of trees and buildings, respectively. The average height is 20 ft. for the building rows and the building percentage is 60% in the study areas. The average height of maple tree zones is 60 ft. The average height of pine tree zones is 40 ft. The ground elevations were determined using a GPS device. Since the GPS evaluations have not been proven reliable, the ground elevations were corrected using the reference points with known elevations and the design drawings. The height of the receiver is 4.92 ft. above the ground. The pavement type is Portland cement concrete (PCC) with transverse tining.

Traffic volume and vehicle categories were determined from the vehicle counts collected using a videotape recorder while performing field noise testing. Traffic speeds were measured using a laser gun. Presented in Figure 6.5 are the photos showing the traffic measuring team member at work. The authors also examined the traffic counts at an automatic traffic recorder (ATR) site close to the project area. The AADT is 132000 with a truck percentage of 18% in March, 2012. The peak hour traffic volume occurred around 7 am westbound and 16 pm eastbound. Table 6.2 shows the final traffic inputs used for the TNM analysis in this study.

The barrier type is Wall. The station, height, length and NRC for each type of the noise wall can be found in Chapters 3 and 4, respectively. It should be noted that other general inputs, including user preferences, including environment humidity, temperature and ground type, may also affect noise prediction using TNM 2.5. Presented in Table 6.3 are the general inputs selected for the TNM noise analysis in this study.

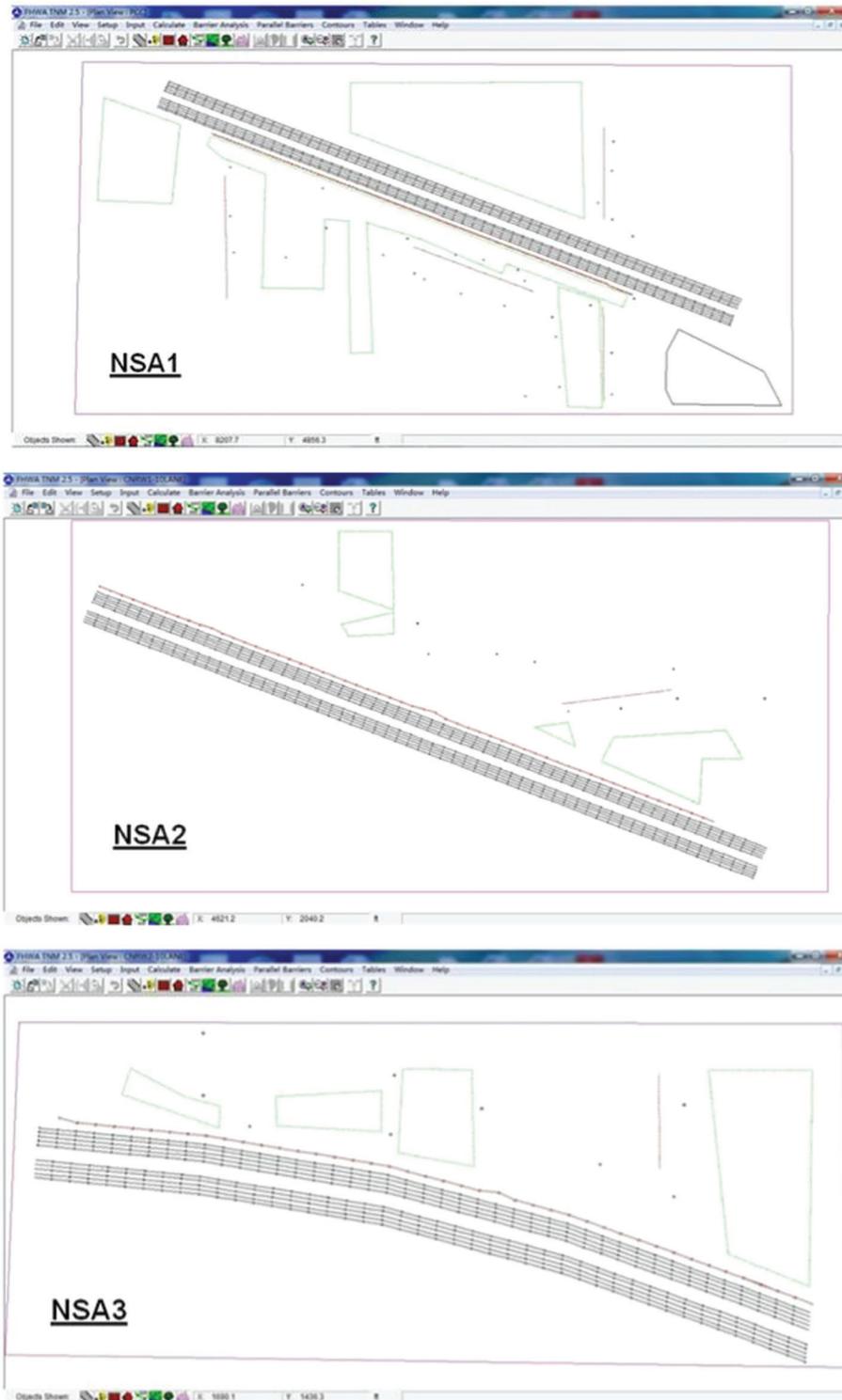


Figure 6.3 Drawings for NSA1, NSA2 and NSA3 in TNM 2.5.



Figure 6.4 Photos showing leveling crew at work.



(a) Videotaping traffic

(b) Recording vehicle speeds

Figure 6.5 Photos of measuring vehicle speeds using laser gun.

6.2 Validation of Prediction Models

6.2.1 Validation Process

As a general rule of thumb, a model is considered valid if the predicted and measured noise levels are within ± 3 dBA in the noise sensitive area (9). Otherwise, the model is not considered valid and must be calibrated in terms of the possible reasons. The calibration of a model can be undertaken in two different ways. First, if the model is consistently over-predicting or under-predicting by greater than 3 dBA, the predicted results can be adjusted simply by the differences between the measured and predicted noise levels. Second, if the differences between the predicted and measured noise levels are caused due to the site

condition, the plan presented in the DXF input file should be modified. There are many circumstances, in which, it may not be possible to identify a specific reason for the discrepancy. The investigator should determine causes for the difference between measured and predicted noise levels and the actual level of the adjustment. In general, discrepancies greater than 3 dBA arise due mainly to that the site condition, such as ground type, climate, pavement and other noise resources, may not be accurately modeled. To minimize the potential errors in noise prediction, the following process was implemented in this study to calibrate the constructed models:

- Compare the measured and predicted noise levels and plot the discrepancies in a map covering the noise sensitive area.

TABLE 6.2
Traffic Volume and Speed

Vehicle Category	Traffic Volume (vehicles/hour/lane)				Speed (mph)	
	Average		Peak hour		EB	WB
	EB	WB	EB	WB		
Auto	735	715	1189	826	62.7	63.3
Medium Truck	95	93	154	107	59.3	57.2
Heavy Truck	5	4	7	5	59.5	56.4

TABLE 6.3
General Inputs

Parameter	TNM Menu	TNM Submenu	Setting
Units	Setup	General	English
Traffic Entry Type	Setup	General	1 Hour Leq
Relative Humidity	Setup	General	50%
Temperature	Setup	General	68 °F
Default Ground Type	Setup	General	Lawn

- Identify the locations with a discrepancy greater than ± 3 dBA and the noise discrepancies around these invalid locations to identify the possible trend and consistence associated with the discrepancies.
- Review field testing conditions, such as test time, day of week, and climate.
- Examine the traffic input and historical traffic data, particularly volume, composition, speed and hourly distribution, to identify possible errors involved in traffic input.
- Conduct field visiting to identify any changes or errors that may be involved in the inputs such as ground zone (type and elevation), building row (height and width), tree zone (height and width), height of noise wall.
- Determine and document the possible reasons if the noise level discrepancies continue to be greater than ± 3 dBA.

6.2.2 Analysis of Noise Discrepancies

Great efforts were made by the research team to calibrate the constructed models through intensive field investigations. Since the model calibration in this study involved both the pre-installation and post-installation models and was made at multiple locations, it became very difficult to construct a model with an allowable discrepancy for both pre- and post-installation under

the same ground condition. As shown in Figures 6.6, 6.7, and 6.8 are the discrepancies between the predicted and measured noise levels in NSA1, NSA2 and NSA3, respectively. The number over the slash line is the noise discrepancy for the pre-installation models and the number below the slash line is that for the post-installation models. The positive number indicates that the predicted noise level is greater than the measured noise level and the negative number indicates that the predicted noise level is less than the measured noise level. In NSA1, the calibration was performed at 28 locations (receivers) for the pre-installation models and 25 locations (receivers) for the post-installation models. In NSA2, the calibration was performed at 10 locations (receivers) for both the pre- and post-installation models. In NSA3, both the pre- and post-installation models were calibrated at 9 locations (receivers).

It is shown that in these three figures, the performance of the constructed prediction model varied from area to area, from model to model, and from pre-installation to post-installation. Table 6.4 shows a summary of the validation results, including the minimum discrepancy (Min), maximum discrepancy (Max), mean, standard deviation (Stdev), root-mean-square (RMS) and 95% confidence interval for all 6



Figure 6.6 Distribution of noise level discrepancies in NSA1.



Figure 6.7 Distribution of noise level discrepancies in NSA2.



Figure 6.8 Distribution of noise level discrepancies in NSA3.

TABLE 6.4
Summary of Model Validation Results (dBA)

Area	Model	Min	Max	Mean	Stdev	RMS	Confidence Interval (95%)
NSA1	Pre-Installation	-8.9	4.4	-0.2	2.6	2.5	(-1.1, 0.8)
	Post-Installation	-4.7	3.3	-1.2	2.3	2.6	(-2.1, -0.3)
NSA2	Pre-Installation	-8.1	-2.2	-5.1	2.0	5.4	(-6.3, -3.8)
	Post-Installation	-6.5	3.6	0.7	3.0	2.9	(-1.2, 2.5)
NSA3	Pre-Installation	-2.1	3.7	1.6	2.2	2.6	(0.2, 3.0)
	Post-Installation	-1.5	2.7	0.8	1.5	1.6	(-0.1, 1.8)

models, including 3 pre-installation models and 3 post-installation models. The greatest mean discrepancy of -5.1 dBA arose from the pre-installation model in NSA2. Apparently, the pre-installation model in NSA2 demonstrates the worst performance and the post-installation model in NSA3 demonstrates the best performance in terms of the mean together with the RMS. The 95% confidence interval for the pre-installation model in NSA2 falls completely outside the valid range of ± 3 dBA. However, the 95% confidence intervals for other models fall within the valid range of ± 3 dBA. The above observations indicate that all constructed models except for the pre-installation model in NSA2 are valid and capable of providing accurate and realistic prediction of noise levels.

To better assess the underlying causes that can contribute to the poor performance of the constructed pre-installation model in NSA2, the discrepancies between the predicted and measured pre-installation noise levels in all three areas are re-plotted in Figure 6.9. In NSA1, the discrepancies are uniformly distributed about the 0-discrepancy axis. In NSA3, the distribution of discrepancies is positively skewed for both the pre- and post-installation models. In NSA2, the distribution of discrepancies is positively skewed for the constructed pre-installation model. However, the distribution of discrepancies is negatively biased for the constructed post-installation model. In NSA2, ground condition, such as surface cover, topography and foliage, varies from location ground cover. The elevation of roadway increases from east to west.

Also, the height of noise wall varies from location to location.

Presented in Table 6.5 are the Pearson correlation coefficient matrices of the discrepancies versus receiver distance, ground elevation and noise wall height. The main reason for conducting Pearson correlation analysis is that in reality, the noise discrepancies fluctuated around the 0-axis. It is shown that the correlation coefficients are all negative for all the three pre-installation models. In other words, the pre-installation noise discrepancies decrease as the receiver's distance increases. However, the correlation coefficients become positive for the post-installation models in both NSA1 and NSA2. This is probably due to the effect of noise walls, which in turn depends on the ground conditions within the areas. The pre-installation noise discrepancies in NSA2 exhibit very poor correlation with the distance and elevation. This indicates that the pre-installation noise model in NSA2 may involve some consistent errors. As a result, this model was adjusted simply by adding 5 dBA, i.e., the average discrepancies, to the predicted value at each receiver.

6.3 Noise Prediction Sensitivity Analysis

6.3.1 Effect of Pavement Type

The pavement type primarily affects sound emissions from TNM vehicles. FHWA TNM 2.5 contains four different pavement types, such as dense graded asphaltic concrete (DGAC), Portland cement concrete (PCC), open graded asphaltic concrete (OGAC), and "Average"

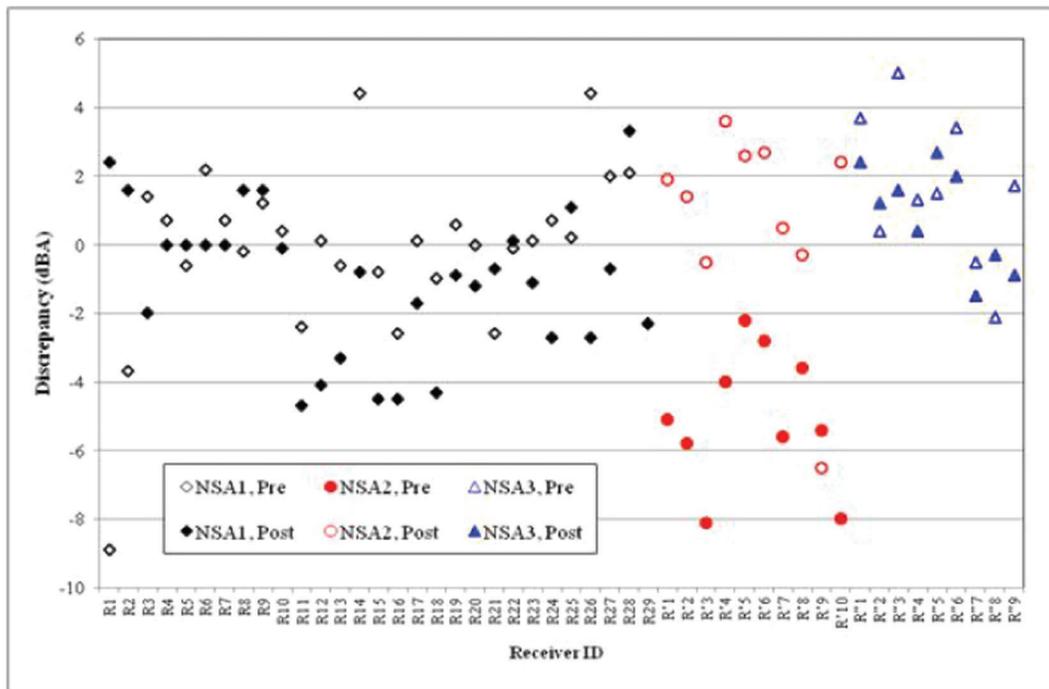


Figure 6.9 Discrepancies between predicted and measured noise levels at each receiver.

TABLE 6.5
Pearson Correlation Coefficient Matrices

Area	Model	Distance	Elevation Difference	Height
NSA1	Pre-Installation	-0.2548	0.1871	—
	Post-Installation	0.5473	0.0624	0.1592
NSA2	Pre-Installation	-0.0222	-0.1649	—
	Post-Installation	0.4939	0.3076	-0.1645
NSA3	Pre-Installation	-0.6115	-0.1011	—
	Post-Installation	-0.2488	0.0976	-0.2420

pavement which is derived from DGAC and PCC data. Table 6.6 shows the noise reductions with DGAC, OGAC and Average pavements, respectively, compared to the reference noise levels predicted using PCC. The noise reduction in the table indicates the arithmetic mean of the noise reductions achieved at all houses in the front row in each area. Apparently, the noise levels predicted with DGAC, OGAC and Average pavements are all lower than those predicted with PCC. The OGAC results in the lowest noise levels regardless of the area and test stage.

In NSA1, the DGAC results in an average noise reduction of 2.9 dBA, the OGAC results in an average noise reduction of 3.5 dBA and the Average pavement results in an average noise reduction of 2.0 dBA at the pre-installation stage. At the post-installation stage, the DGAC, OGAC and Average pavements also provides noise reductions in all areas. However, the amount of noise reduction decreases when compared to the noise reductions at the pre-installation stage due to the effect of noise walls. The average noise reductions become 2.0 dBA, 2.4 dBA and 1.3 dBA for DGAC, OGAC and Average pavements, respectively. Similar observations can also be made in NSA2 and NSA3. Also, the noise reductions by the OGAC are perceptible at the pre-installation stage in all three areas. The prediction results agree with a statement (54), “Studies have shown open-graded asphalt pavement can initially produce a benefit of 2-4 dBA reduction in noise levels.” Some pavements may provide noise reductions perceptible to the human ear.

TABLE 6.6
Noise Reduction by Pavement Type

Area	Test Stage	Decrease in Noise Level (dBA)		
		DGAC	OGAC	Average
NSA1	Pre-Installation	2.9	3.5	2.0
	Post-Installation	2.0	2.4	1.3
NSA2	Pre-Installation	2.3	2.9	1.5
	Post-Installation	1.7	2.6	1.1
NSA3	Pre-Installation	2.6	3.1	1.8
	Post-Installation	1.3	1.8	0.8

6.3.2 Effect of Traffic

In order to investigate the potential effect of traffic speed on the noise levels in the three noise sensitive areas, this study computed the pre- and post-installation noise levels by varying the traffic speed from 50 mph to 75 mph. As shown in Figures 6.10 and 6.11 are the computed noise levels for the houses in the front rows in the three areas at both the pre- and post-installation stages, respectively. It is shown that in NSA1, as traffic speed increases, the computed noise levels increase proportionally regardless of the test stage. Also, the rate of noise rate at the pre-installation stage is slightly greater than that at the post-installation stage. The noise levels increase by around 5 dBA when traffic speed increases from 50 mph to 75 mph, i.e., approximately 1 dBA per 5 mph increase in traffic speed. The predicted noise levels are all below 66 dBA at 55 mph.

Similar observations can be made in NSA2 and NSA3. In general, the noise increase per 5 mph is around 1 dBA at the pre-installation stage and 0.9 dBA at the post-installation stage in all three noise sensitive areas. Also, the average noise increases due to an increase in traffic speed are very close in these three areas. This may be used to conclude that the effect of traffic speed on the noise level is independent of the ground condition to some extent and is probably dependent on the noise prediction methodologies utilized by TNM 2.5. While the noise level increases as traffic speed increases, the effect of lowering traffic speed may be negligible in the project area. In reality, the posted speed limit is already 55 mph on I-465. It may not be feasible to abate traffic noise through further lowering the posted speed limit, particularly after installing the noise walls.

The authors also computed the noise levels in different traffic volumes, i.e., the variation of noise level over the design year. Presented in Table 6.7 are the results at the pre-installation stage in NSA1, NSA2 and NSA3, respectively. The design life was assumed to be 20 years for all noise walls installed in the project area. The traffic growth rate was assumed to be 2% per year. As the service life of the noise wall increases, traffic volume increases. As a result, the noise level increases. However, the noise levels increase only by approximately 1.7 dBA from the first year to the design year regardless of the area. In other words, the traffic noise level increases by

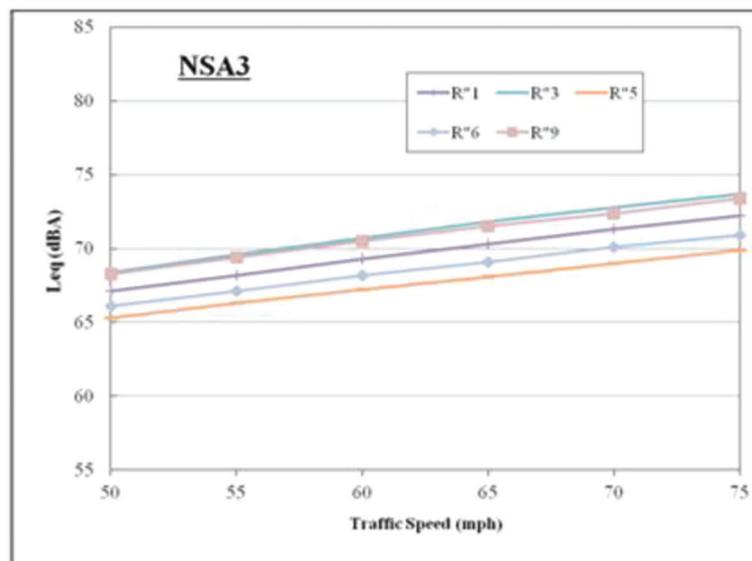
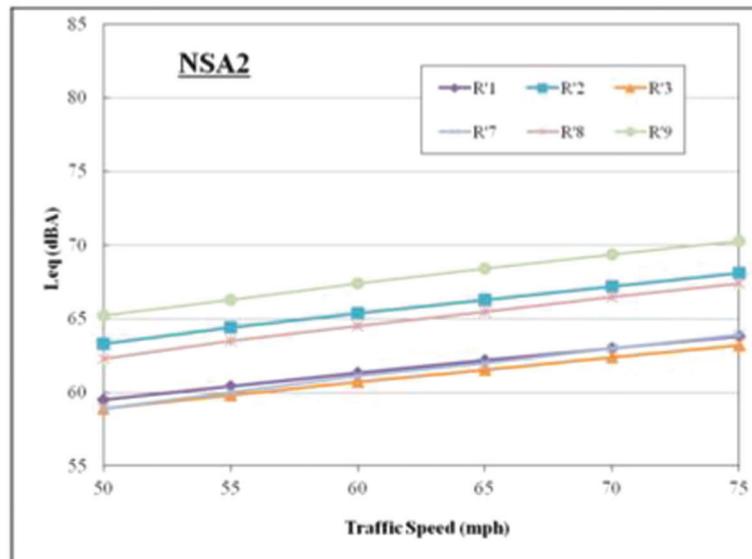
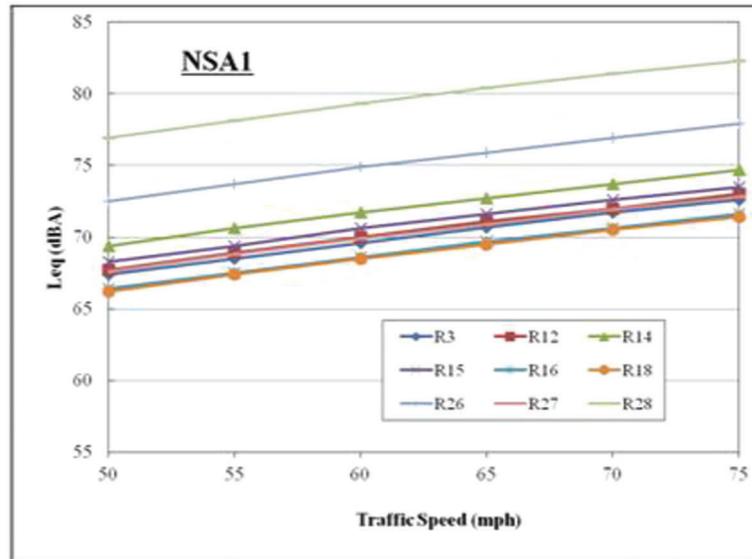


Figure 6.10 Variation of pre-installation noise level with traffic speed.

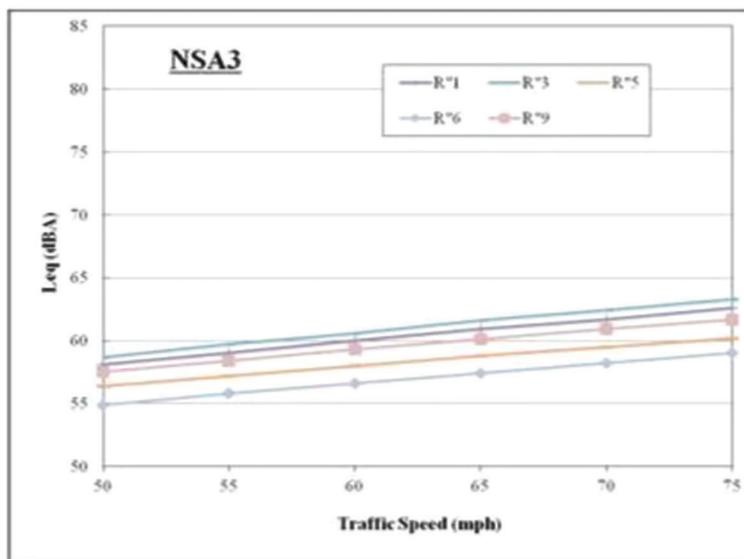
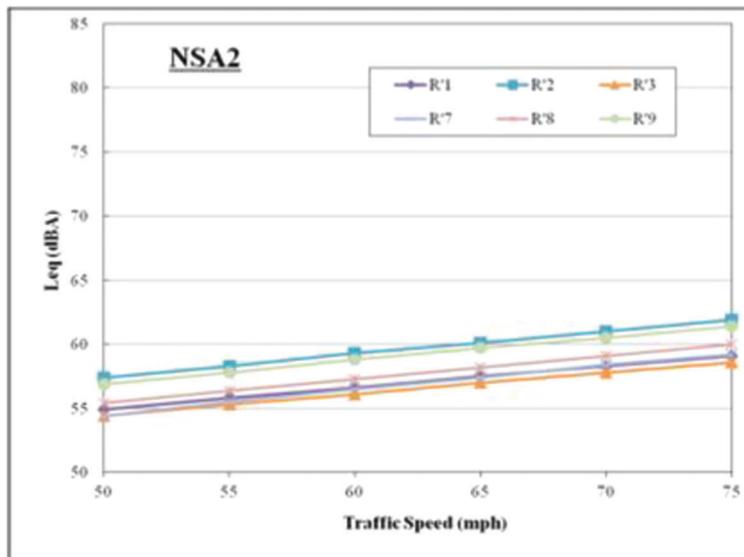
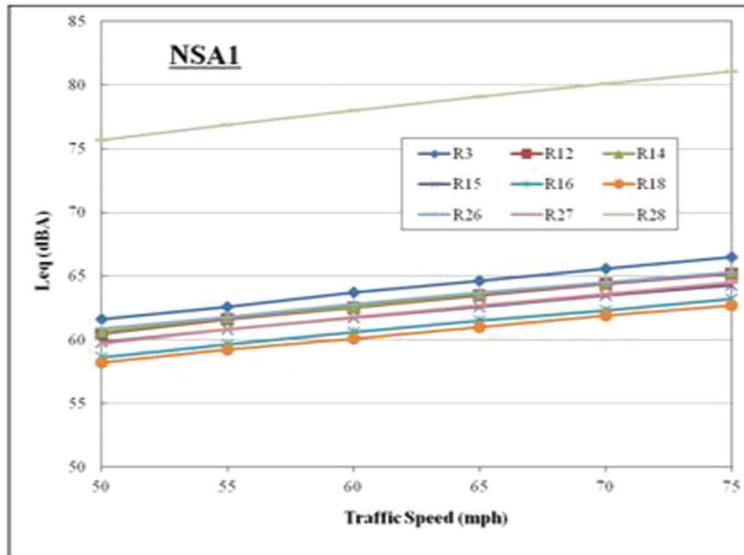


Figure 6.11 Variation of post-installation noise level with traffic speed.

TABLE 6.7
Variations of Pre-Installation Noise Levels over Design Year (dBA)

Area	Receiver	Time (years)				
		0	5	10	15	20
NSA1	R3	70.0	70.5	70.9	71.3	71.7
	R12	70.4	70.8	71.3	71.7	72.1
	R14	72.1	72.5	72.9	73.4	73.8
	R15	70.9	71.4	71.8	72.2	72.6
	R16	69.0	69.4	69.9	70.3	70.7
	R18	68.9	69.3	69.7	70.2	70.6
	R26	75.3	75.7	76.1	76.6	77.0
	R27	70.3	70.7	71.1	71.6	72.0
	R28	79.7	80.1	80.6	81.0	81.4
NSA2	R'1	61.6	62.1	62.5	62.9	63.3
	R'2	65.7	66.2	66.6	67.0	67.4
	R'3	61.0	61.4	61.8	62.3	62.7
	R'7	61.4	61.9	62.3	62.7	63.1
	R'8	64.9	65.3	65.8	66.2	66.6
NSA3	R'9	67.8	68.2	68.7	69.1	69.5
	R"1	69.7	70.1	70.5	71.0	71.4
	R"3	71.1	71.6	72.0	72.5	72.9
	R"5	67.5	68.0	68.4	68.9	69.3
	R"6	68.5	68.9	69.4	69.9	70.3
	R"9	70.9	71.3	71.7	72.2	72.6

less than 0.1 dBA each year. Similar to the effect of traffic speed, the effect of traffic volume on the noise level is also independent of the ground condition, which is solely due to the noise prediction methodologies used by TNM 2.5.

Similar observation can be made about the effect of traffic volume on the post-installation noise level (see Table 6.8). Traffic noise has long been perceived by the public to increase remarkably with increased volumes and varies significantly between peak and off-peak hours. Nevertheless, based on the fundamentals of acoustics (55), a reduction in sound energy of 50% results in a reduction of 3 dB and is just perceptible to the normal human ear. In other words, doubling the sound energy (e.g., doubling the traffic volume) may result in a 3 dBA increase in sound level. It is already shown by the field noise measurements (see Chapter 4) that the difference between the peak and off-peak hour noise levels is less than 2 dBA in the project area. Notice that the I465 segment in the project area carries high traffic flow with 132000 AADT. As traffic volume increases, the road becomes more congested, which may result in a reduction in traffic speed. Consequently, the effect of traffic on the noise variation may be neglected in the project area.

6.3.3 Effect of Noise Wall Characteristics

As shown in Chapter 3, the NRC is 0.85 for the Durisol precast panels in NSA2 and NSA3. The NRC is 0.75 for both the Noise D-Fence and Sanders precast

panels in NSA1. The AAC noise barrier panels are reflective panels. In order to evaluate the effect of NRC on the noise reduction performance, the authors investigated the relationship between the noise level and NRC using the post-installation noise model in NSA1. Presented in Figure 6.12 are the computed noise levels at the front row houses. The NRC varies from 0 (perfectly reflective) to 1.0 (perfectly absorptive). It is shown that as NRC increases, the computed noise levels decrease. However, the amount of noise reduction is completely negligible. The total amount of noise reduction is 0.2 dBA when the NRC increases from 0 to 0.95. This indicates that the Durisol precast, AAC, Noise D-Fence and Sanders precast panels may provide similar acoustic performance to the protected side.

Figure 6.13 shows the variations of the noise levels with the height of noise wall at the front row houses in the three areas. As the noise wall height increases from 10 ft. to 24 ft., the noise level decreases by an average 5.6 dBA in each area, respectively. The decrease rate drops as the noise wall height increases, particularly when the noise wall exceeds 16 feet high. The effectiveness of noise reduction by increasing the noise wall height varies with the receptor's distance and elevation. The noise reduction decreases as the distance increases or as the elevation decreases. The noise reduction at the end of noise wall (see R3 and R27) is less than the noise reduction in the middle of noise wall. Figure 6.14 shows the average noise reductions at 2-foot increment from the height of initial noise wall. For example, when the height of noise wall increases from

TABLE 6.8
Variations of Post-Installation Noise Levels over Design Year (dBA)

Area	Receiver	Time (years)				
		0	5	10	15	20
NSA1	R3	64.0	64.4	64.8	65.3	65.7
	R12	62.9	63.3	63.7	64.1	64.5
	R14	62.9	63.3	63.7	64.2	64.6
	R15	62.0	62.4	62.8	63.3	63.7
	R16	60.8	61.2	61.6	62.1	62.5
	R18	60.4	60.8	61.2	61.7	62.1
	R26	63.0	63.5	63.9	64.3	64.7
	R27	62.1	62.5	62.9	63.4	63.8
	R28	78.5	78.9	79.3	79.7	80.1
NSA2	R'1	57.0	57.4	57.8	58.3	58.7
	R'2	59.6	60.0	60.4	60.9	61.3
	R'3	56.5	56.9	57.3	57.8	58.2
	R'7	56.8	57.3	57.7	58.1	58.5
	R'8	57.7	58.1	58.5	58.9	59.3
	R'9	59.1	59.5	59.9	60.4	60.8
NSA3	R''1	60.3	60.7	61.1	61.6	62.0
	R''3	61.0	61.4	61.8	62.2	62.7
	R''5	58.3	58.7	59.1	59.6	60.0
	R''6	56.9	57.3	57.7	58.2	58.6
	R''9	59.5	60.0	60.4	60.9	61.3

16 ft. (the initial height on horizontal axis) to 18 ft., the average noise reductions are 0.62 dBA, 0.73 dBA and 0.76 dBA in NSA1, NSA2 and NSA3, respectively. The noise reduction decreases as the height increases, particularly when the wall height exceeds 16 feet.

It is perceived that by the residents, particularly those living to the ends of the LOS walls in NSA1, the noise wall should be made longer to provide more noise reductions. This study first examined the effect of the

length of noise wall on the noise levels at R1, R2 and R3 in NSA1. As indicated in the previous chapters, R1, R2 and R3 are located along Haverstick Road and close to the east end of the LOS wall made out of the Sanders precast panels. Figure 6.15 shows the resulting noise levels at R1, R2 and R3 by extending the Sanders LOS wall east. It is shown that as the Sanders LOS wall extends further east, the noise levels decrease at all three locations. Nevertheless, the amount of noise reduction

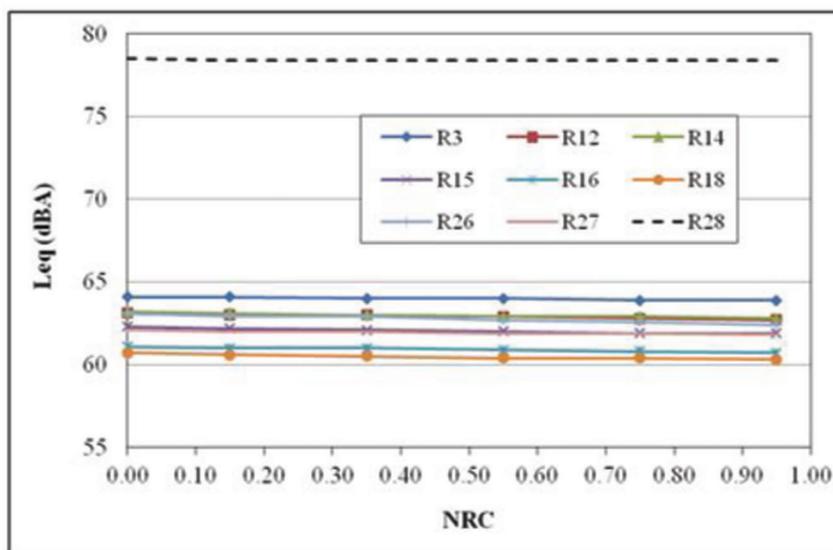


Figure 6.12 Variation of noise level with noise wall NRC in NSA1.

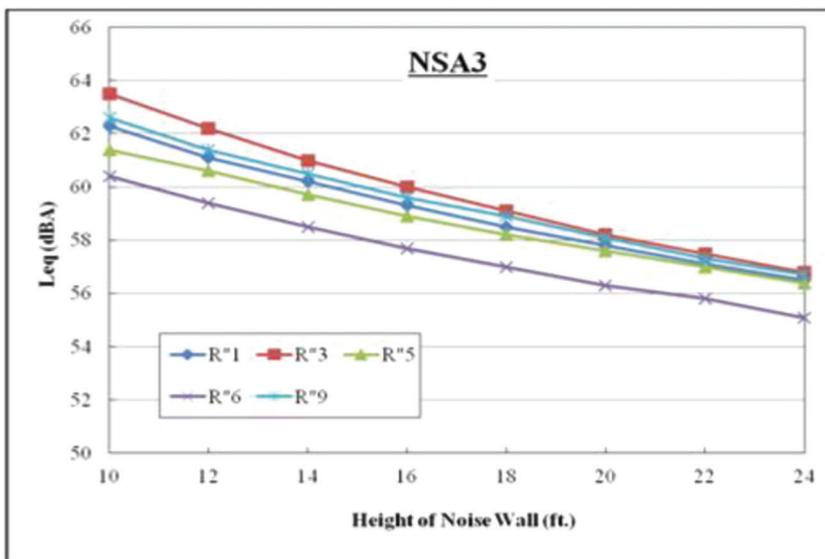
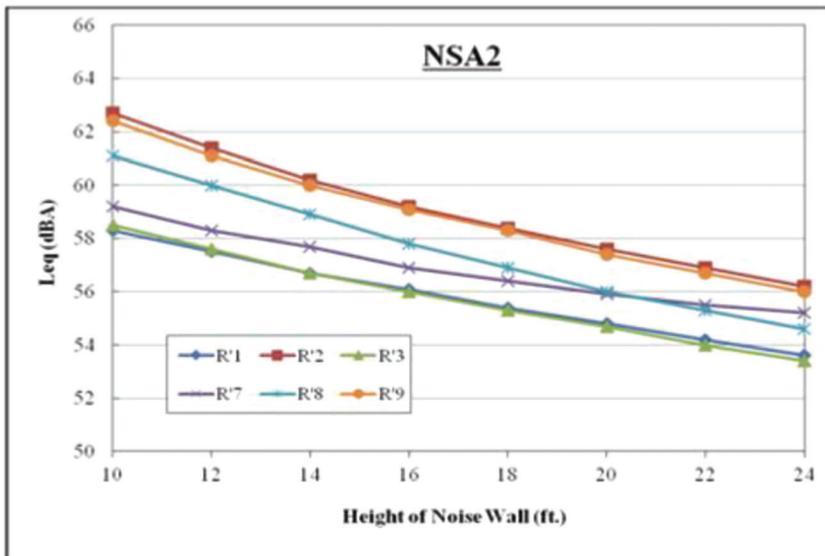
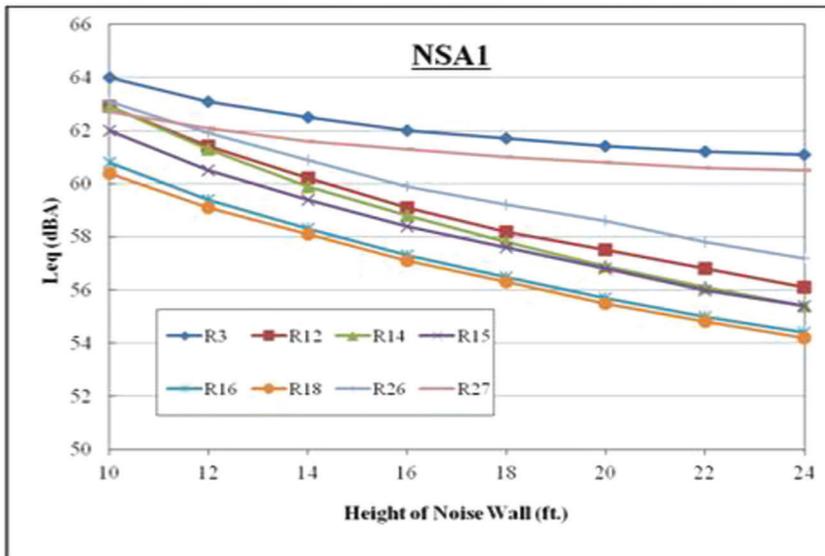


Figure 6.13 Variation of noise level with noise wall height.

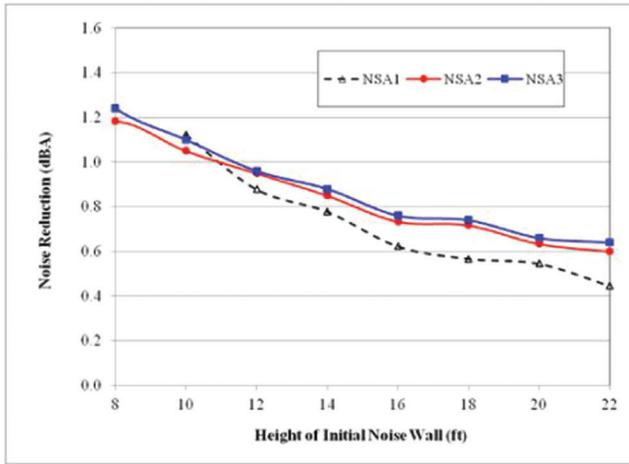


Figure 6.14 Noise reduction at 2-foot increment in noise wall height.

is negligible at all three locations. When the Sanders LOS wall is extended 30 ft. east, the noise reduction is 0.2 dBA, 0.3 dBA and 0.3 dBA at R1, R2 and R3, respectively, an average noise reduction of 0.27 dBA. This study further evaluated the effect of the length of AAC noise wall on the noise level at R27. A noise reduction of 0.5 dBA can be achieved by extending the AAC wall 30 ft. west. It was also shown that when the Sanders LOS wall is extended further, the reduction rate of noise decreases slightly. In other words, making the Sanders or AAC LOS wall in NSA1 longer may not provide noise reduction as much as expected at those houses living close to the ends of LOS walls.

In general, a noise wall should be long enough so that the distance between a receiver and a noise end is at least four times the perpendicular distance from the receiver to the noise wall (56). If a barrier is not long

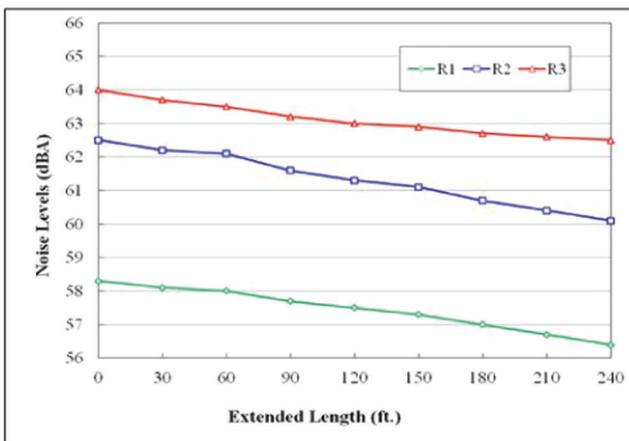


Figure 6.15 Noise level versus extended wall length.

enough, the noise reduction performance may degrade by up to 5 dBA. However, this depends on the real site situation. In reality, while R3 is located right behind the Sanders LOS wall, its noise reduction is less than those at R2 and R3 which are located further from the Sanders LOS wall. The greatest noise occurs at R2 located between R1 and R3. As indicated in Chapter 4, there is a free, open field between Haverstick Road and the I-465 off-ramp to Keystone Avenue. The traffic noise from I-465 between Haverstick Road and the Interchange may have some impacts on the houses at R1, R2 and R3. Consequently, making the Sanders LOS wall longer may be less cost effective in abating the traffic noise at R1, R2 and R3.

6.4 Predicted Noise Reduction Effectiveness

6.4.1 N66 Noise Distributions

In the old and existing INDOT traffic noise polices, a noise receiver is identified as “impacted” when the predicted noise level approaches or exceeds the NAC, i.e., when the predicted noise level is equal to or greater than 66 dBA. Presented in Figures 6.16, 6.17 and 6.18 are the predicted pre- and post-installation N66 noise distributions in NSA1, NSA2 and NSA3, respectively. The N66 distributions were derived from the noise impact criteria of 66 dBA, which indicate a region about the noise sensitive area, within which the noise level is equal to or greater than 66 dBA. It is well known that noise distributions have found many attractive applications, such as noise impact analysis, land use planning, and noise abatement assessment. The use of N66 noise distributions in this study was intended to provide a full picture to visualize the total noise exposure and impact in the noise sensitive area.

It can be seen that in Figure 6.16, the N66 noise distribution at the pre-installation stage is a flat rectangle along I-465. The two long sides are relatively straight. The building row between I-465 and North Temple Avenue and part of the building row on Haverstick Road, i.e., R3, R12, R14, R15, R16, R18, R26 and R27, are enclosed within the N66 distribution. After installing the LOS walls, the N66 noise distribution remains unchanged on the north of I-465. On the south of I-465, the shape of the N66 noise distribution has changed. The long side moves toward to I-465, resulting in a smaller N66 noise distribution area. The building row between I-465 and North Temple Avenue is now located outside the N66 noise distribution. Only R28 at the end of Haverstick Road remains enclosed within the N66 noise distribution.

Similar observations can be made about NSA2 and NSA3 from Figures 6.17 and 6.18. In general, the N66 noise distributions in the three noise sensitive areas are flat rectangles with relatively long sides parallel to I-465 before the installation of noise walls. Some receivers are enclosed within the N66 noise distributions. After installing the noise walls, the shapes of N66 noise distributions have changed. The N66 noise distribution

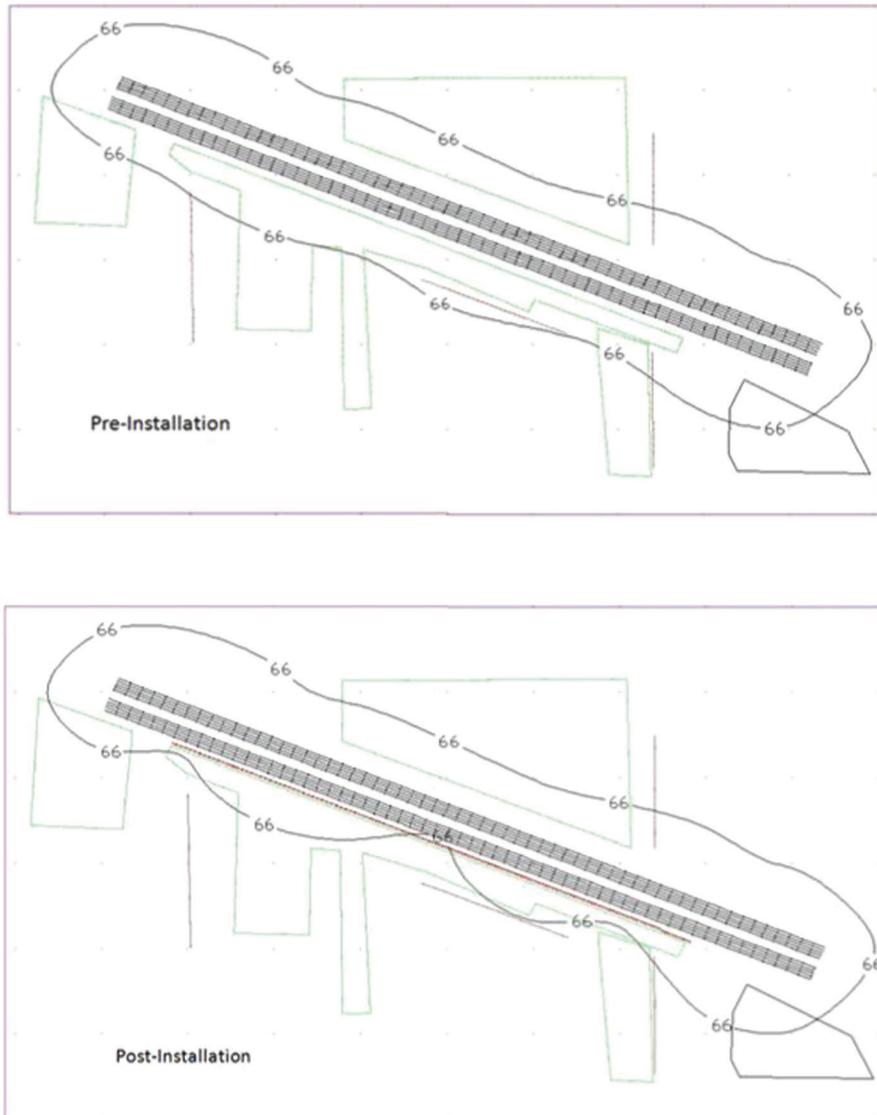


Figure 6.16 Pre- and post-installation N66 distributions in NSA1.

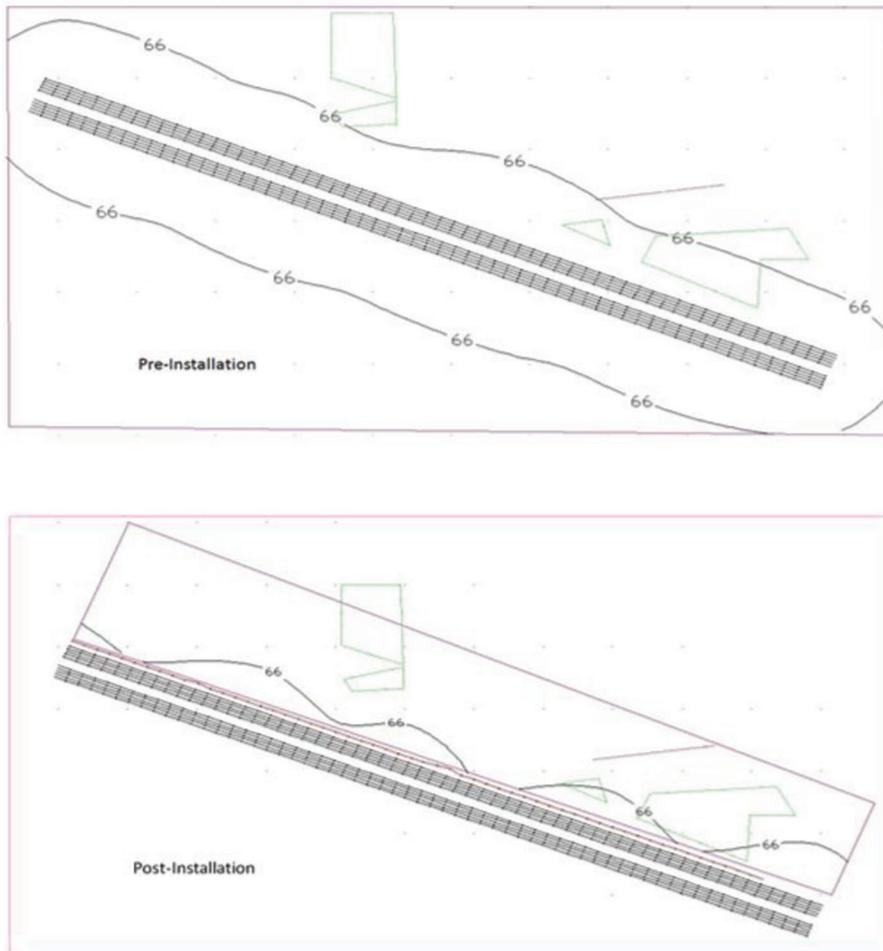


Figure 6.17 Pre- and post-installation N66 distributions in NSA2.

line on the protected side moves much closer to I-465 at different locations. As a result, the N66 noise distribution area has become much smaller. In reality, it is shown that in Figures 6.9, 6.17 and 6.18, most of the receivers (see the building rows) in the three study areas are located well outside the N66 noise distributions after installing the noise walls.

6.4.2 Noise Reduction Effectiveness

It has been widely accepted that effective noise walls typically reduce noise levels by 5 to 10 dBA (5). INDOT requires that noise barriers achieve a 5 dBA reduction at a majority (greater than 50%) of the impacted receptors (15). This study has examined the noise reduction effectiveness by assuming a noise reduction (insertion loss) threshold of 5 dBA accordingly. However, the noise reduction effectiveness is measured using the percentage of the selected receivers, which receives a noise reduction equal to or greater than the 5 dBA threshold. Presented in

Figure 6.19 are the noise reductions predicted using TNM 2.5 right after the completion of noise wall installation at the selected receivers in NSA1, NSA2 and NSA3, respectively. The average noise reductions are 4.4 dBA, 11.4 dBA and 8.7 dBA in NSA1, NSA2 and NSA3, respectively. In NSA1, 9 out of 21 receivers (43%) exhibit a noise reduction of 5 dBA or more. In NSA2, all 10 receivers (100%) receive a noise reduction of well above the 5 dBA threshold. In NSA3, all 9 receivers (100%) achieve noise reduction above the 5 dBA threshold.

Presented in Table 6.9 are a summary of the noise reduction effectiveness predicted over the design year. It is shown that in NSA1, the percentage of receivers with a noise reduction of 5 dBA or more decreases as the service life increases. The decreasing rate in the early or late service life is much greater than that in the middle of design year. In the end of design year, only 33% of the receivers in NSA1, 56% of the receivers in NSA2 and 100% of the receivers in NSA3 can achieve a noise reduction of 5 dBA or more.

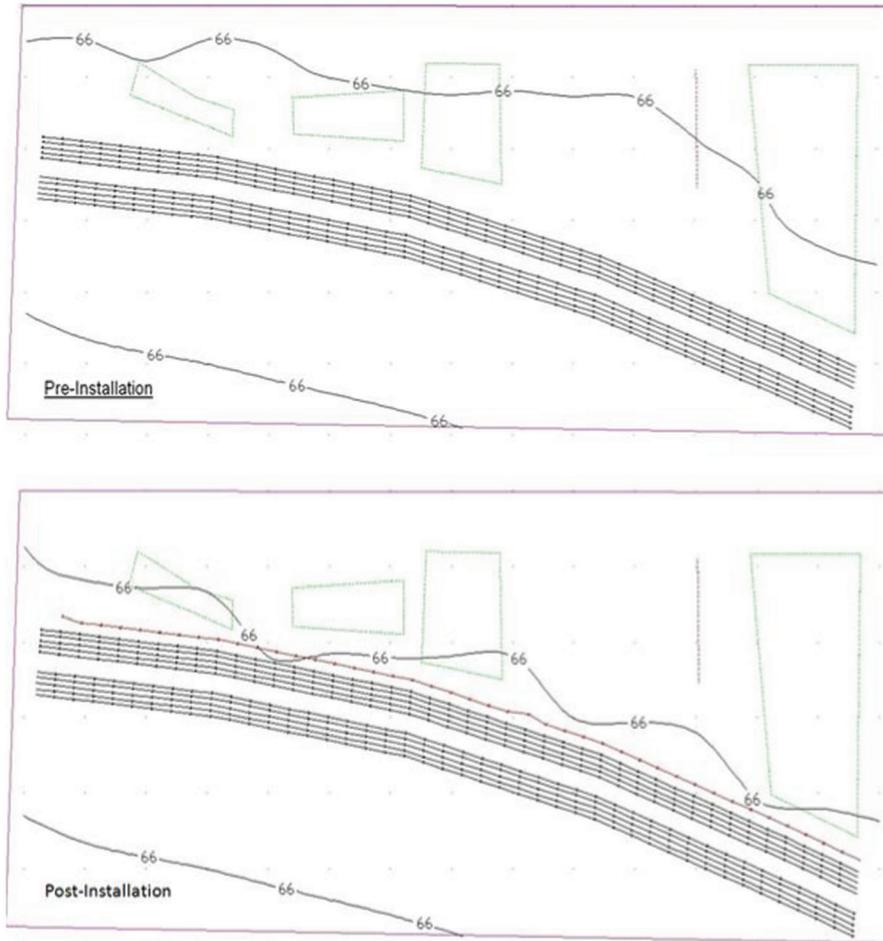


Figure 6.18 Pre- and post-installation N66 distributions in NSA3.

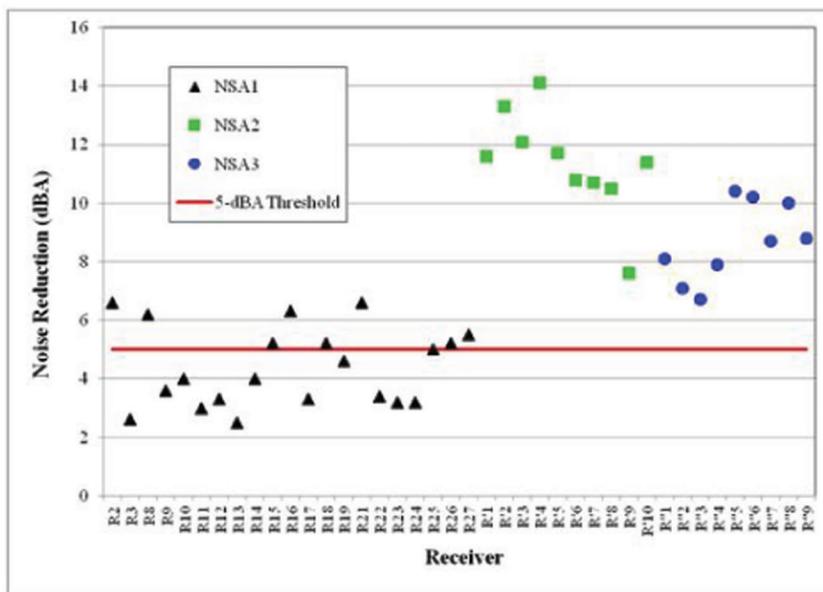


Figure 6.19 Noise reductions achieved right after installing noise wall.

TABLE 6.9
Summary of Noise Reduction Effectiveness over Design Year

Area	% of Receivers with Noise Reduction \geq 5 dBA				
	0-Year	5-Year	10-Year	15-Year	20-Year
NSA 1	62%	48%	48%	38%	33%
NSA 2	67%	56%	56%	56%	56%
NSA 3	100%	100%	100%	100%	100%

7. PRE- AND POST-INSTALLATION COMMUNITY NOISE SURVEYS

7.1 Survey Design and Execution

7.1.1 Survey Purposes

Two community noise surveys, including pre- and post-installation noise surveys, were conducted as one of the community outreach activities to address the residents' concerns on the agency's traffic noise strategies. The pre-installation community noise survey was conducted in the residential communities before the installation of the noise walls in all three noise sensitive areas. The primary purposes of this survey were threefold. First, the pre-installation survey aimed at identifying the impact of the existing traffic noise on the communities. Second, as the economy grows, traffic volume and resulting noise continues to grow. This pre-installation survey was anticipated to assist INDOT in understanding the residents' expectations for a cost-effective solution to traffic noise reduction. Third, as the community's concern over traffic noise is growing, a successful, sustainable noise reduction plan requires the involvement of a number of stakeholders, including state agencies, cities, private sectors, and residents. The pre-installation survey attempted to estimate the residents' willingness to pay (WTO) for a proposed measure for abating noise reduction in their communities.

The post-installation community noise survey was conducted after the installation of all proposed noise walls in all three noise sensitive areas. The purposes of the post-installation survey were also threefold, and nevertheless different from those of the pre-installation survey. First, the post-installation survey was to gain the perception of the residents on the noise reductions. Second, this survey was to assess the residents' satisfaction with the three LOS walls, including AAC, Noise D-Fence and Sanders precast walls compared to the conventional concrete noise walls. Third, the post-installation survey was conducted to gather the residents' view on the appearance of the selected LOS walls, particularly the geometric and aesthetics features. It was believed that a comparison between the pre- and post-installation survey results might be a more effective approach to assess the effectiveness of the noise walls in abating the traffic noise.

7.1.2 Survey Questionnaires

The survey questionnaires were created to contain mainly structured questions that offer the respondents a closed set of responses from which to choose. For the pre-installation survey, there were a total of 26 questions which were divided into four categories (see Appendix A). The first category consists of 5 questions to gain general information on the respondents, such as age, gender, length of residence, housing type, home ownership and household. The second category is comprised of 3 questions to determine the residents' views on the change in traffic volume and truck traffic before installing the noise walls, and their priorities for traffic impact, such as traffic volume, noise, congestion, emissions, and safety. The third category consists of 9 questions designed to gauge the information on how and when the traffic noise were currently affecting the residents' life. The fourth category contains 9 questions to capture the residents' opinions on federal noise regulations and INDOT traffic noise policy, expectations for traffic noise reduction, and willingness to pay for a proposed noise abatement measure.

The post-installation community noise survey consists of a total of 19 questions (see Appendix B). These questions were carefully designed to match the questions in the pre-installation survey and also divided into four categories. The first category consists of 5 questions that are the same questions in the first category in the pre-installation survey. The second category consists of only 1 question to determine the truck traffic condition before and after installing the noise walls. The third category contains 7 questions to assess the noise impact after installing the noise walls. Since the addresses of the respondents were marked in the post-installation survey, these 7 questions were also used to evaluate the effectiveness of noise reduction provided by different walls. The fourth category consists of 6 questions designed to provide insights into the residents' perceptions on the noise wall appearance (aesthetics and geometric feature) and the residents' general concerns.

7.2 Survey Execution and Response

7.2.1 Survey Execution

Both the pre- and post-installation community noise surveys were executed via the mail. There were four main reasons for the authors to conduct the surveys via the mail. First, the addresses of the residents in the project were readily available from a previous study (33). Second, the potential residents who might receive traffic impacts had already been identified in the previous study. The mail survey could not only encourage honest answers and obtain possible negative feedbacks, but also avoid potential awkward social situations which might arise in a telephone survey or one-on-one interview. Third, some questions raised delicate issues which were important to both the agency

and the respondents. Some other questions might also be difficult for the respondents to answer. The mail survey might provide the respondents time flexibility to answer. Fourth, the pre-installation survey consisted of 4 pages of questionnaire and the post-installation survey consisted of 3 pages of questionnaire, which might be a great burden to the respondents, particularly for telephone survey and one-on-one interview.

The pre-installation community noise survey started on March 31, 2011, respectively. A total of 120 letters, each enclosing a self-addressed, stamped envelope, were sent out to 58 apartment homes and 62 single family houses, of which 96 letters were forwarded to the residents in the project area. A pre-notification was added before the questionnaire field to indicate the purpose of survey and privacy. The deadline was April 30, 2011, providing the residents a full month of response time. The post-installation community noise survey was carried out on July 25, 2012, and the survey deadline was August 4, 2012. An address indicator was added to the survey letter to allow the research team to identify the link between a specific response and the respondent's location. The survey letters were mailed to 71 homes in NSA1 and 55 homes in NSA2 and NSA3, respectively. A total of 112 letters were successfully forwarded to the residents, including 59 residents in NSA1 and 53 residents in NSA2 and NSA3.

7.2.2 Response Rate

It has long been assumed that the higher the response rate, the more accurate the survey results. There are several techniques that can be utilized to influence the response rate positively (57). However, a low response rate does not necessarily mean that the survey results are biased (58). A low response rate is commonly defined as that lower than 20% (59). Summarized in Table 7.1 are the sample sizes, response rates, and costs for both the pre- and post-installation surveys. It is shown that the response rate for the pre-installation survey is 40.6%. For the post-installation survey, the response rate is 38.4%. This is probably due to the time of survey. The post-installation survey started in July, i.e., during the school summer vacation. Both the pre- and post-installation survey rates are higher than what the research team expected. This is probably due to the fact that traffic noise has been perceived as one of the most negative impacts of transportation on the quality of life for residents living close to highways.

In reality, the authors utilized three techniques, such as enclosing a self-addressed, stamped envelope, providing a pre-notification to highlight confidentiality and importance, and giving the survey deadline, to increase the response rates. The authors particularly examined response time and the effect of deadline on the response rates. Plotted in Figure 7.1 are the cumulative distributions of response time for the pre- and post-installation surveys, respectively. It is shown that the cumulative distribution curve for the post-installation survey lags behind that for the pre-installation survey. This is due mainly to the effect of the post-installation survey time. However, both curves follow a similar trend, varying dramatically over the first three weeks, and gradually afterwards. Over 40% of the responses arrived within one week, around 70% of the responses arrived within two weeks, and over 80% of the responses arrived within three week. This indicates that the responses returned rapidly within the first three weeks, and tapered off after three weeks in both the pre- and post-installation surveys.

Commonly, deadlines should increase response rates due to the perception of scarcity (60,61). In this study, the survey recipients were given 30 days for the pre-installation survey and 11 days for the post-installation survey to return their responses. Table 7.2 shows the statistics of the survey response deadline, rate and time. The pre-installation survey yielded a higher response rate and a faster response time than the post-installation. Two sample t-test and F-test (62) were conducted to test for the differences of the response times between the pre- and post-installation surveys. Neither of the null hypothesis of equal means nor the null hypothesis of equal variances was rejected at a confidence level of 95% (see Figure 7.2). Notice that in the tests, the response time was assumed to have a log-normal distribution. Therefore, there was no evidence to show the effect of the survey deadline on the response pattern. Based on the responses, it is likely that a run time of 3 weeks may be sufficient for conducting a community survey on traffic noise.

7.3 Survey Results and Analysis

7.3.1 Demographic Factors

To the authors' knowledge, the factors such as age and gender may play an important part in the residents' awareness of the traffic noise issues and affect the

TABLE 7.1
Survey Sample Sizes, Response Rates, and Costs

Time of Survey	No. of Mails Sent	No. of Mails Delivered	Response Rate	Stamp Cost
Pre-Installation	120	96	40.6%	\$95.04
Post-Installation	126	112	38.4%	\$104.72

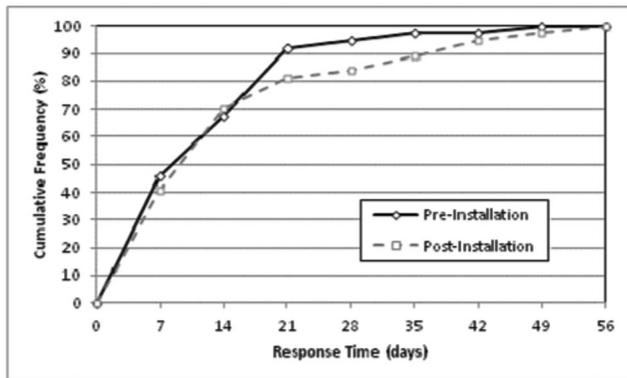


Figure 7.1 Survey response time cumulative distributions.

residents' views on the impact of traffic noise and abatement measures. Therefore, both the pre- and post-installation surveys include a question to identify the respondent's age, gender, residency length, housing type, home ownership, and household. Presented in Figure 7.3 are the age distributions of the respondents for the pre- and post-installation surveys, respectively. Apparently, the age distribution for the pre-installation is different from that for the post-installation. The respondent ages for the post-installation survey distributed more evenly than those for the pre-installation

survey. In the pre-installation, young adult (20 to 40), middle aged (40 to 60) and elderly respondents (over 60) accounted for 26.3%, 39.5% and 34.2% of all respondents, respectively. In the post-installation survey, young adult, middle aged and elderly respondents accounted for 23.3%, 30.2% and 46.5% of all respondents, respectively. The greatest discrepancies occurred in the 50 to 60 and 60 to 70 age categories.

Summarized in Table 7.3 are the statistics of the respondent age and gender. The respondents in the post-installation survey were generally older than the respondents in the pre-installation survey. The highest concentration of respondents was in the 50 to 60 age category in the pre-installation and in both the 50 to 60 and 60 to 70 age categories. Also, the percent of female respondents increased from 39.5% in the pre-installation survey to 48.8% in the post-installation survey. However, the percent of male respondents decreased by 9.7%. In order to investigate the factors resulting in the differences, the authors examined the age and gender distributions in terms of the noise sensitive area in the post-installation survey. Presented in Table 7.4 are the statistics of the respondent age and gender by area for the post-installation survey. Comparison of the statistics in Tables 7.3 and 7.4 indicates that the demographic factors of the respondents in NSA1 might have

TABLE 7.2 Summary of Survey Response Deadline, Rate and Time

Time of Survey	No. of Days before Deadline	Response Rate	Response Time (days)			
			Min.	Max.	Mean	Stdev.
Pre-Installation	30	40.6%	3	46	12.1	9.6
Post-Installation	11	38.4%	4	52	14.5	12.2

TWO-SAMPLE T TESTS FOR PRE VS POST				
VARIABLE	MEAN	SAMPLE SIZE	S.D.	S.E.
PRE	2.2450	37	0.6990	0.1149
POST	2.3906	37	0.7458	0.1226
DIFFERENCE	-0.1456			
NULL HYPOTHESIS: DIFFERENCE = 0				
ALTERNATIVE HYP: DIFFERENCE <> 0				
ASSUMPTION	T	DF	P	95% CI FOR DIFFERENCE
EQUAL VARIANCES	-0.87	72	0.3892	(-0.4806, 0.1894)
UNEQUAL VARIANCES	-0.87	71.7	0.3892	(-0.4806, 0.1894)
TESTS FOR EQUALITY OF VARIANCES	F	NUM DF	DEN DF	P
	1.14	36	36	0.3495
CASES INCLUDED 74		MISSING CASES 0		

Figure 7.2 Summary of survey response deadline, rate and time.

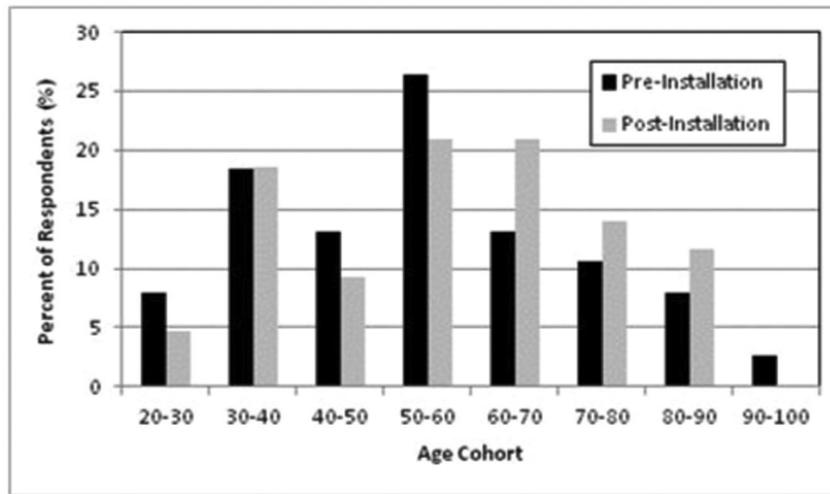


Figure 7.3 Survey respondent age distributions.

played an important role in resulting in the differences in the demographic characteristics.

7.3.2 Housing Characteristics

Figure 7.4 shows the distributions of respondents' length of residency for the pre- and post-installation surveys, respectively. The differences mainly arose associated with the respondents with small numbers of years of residency. This is probably due to the variations arising with the respondents in NSA2. It was stated that in the previous chapters, NSA2 consists solely of an apartment complex and the residents are all apartment renters. Table 7.5 shows the statistics of length of residency by the type of home ownership, including the renter-occupied home and owner-occupied home. The length of residency of the respondents for the renter-occupied homes is much shorter than that for the owner-occupied homes. The average length of residency is slightly over 20 years for the respondents

owning homes, regardless of the time of survey. The tenant turnover rate for the apartment housing property was around 2.8 years for both the pre- and post-installation surveys. However, the average lengths of residency are almost the same for the respondents under the same homeownership in the pre- and post-installation surveys. This may be extended to conclude that both the pre- and post-installation surveys consisted mainly of the same respondents. For the respondents from the renter-occupied homes, the length of residency demonstrated a greater standard deviation in the post-installation survey than that in the pre-installation survey. This is due to the possible tenant turnover during the summer.

To further investigate the effect of home ownership on the response rate, the authors examined the addresses for the survey receivers and survey respondents. Presented in Figure 7.5 are the response rates by the type of home ownership in the pre- and post-installation surveys, respectively. As stated earlier, the

TABLE 7.3
Statistics of Respondent Age and Gender

Time of Survey	Age (years)					Gender (%)	
	Min.	Max.	Mean	Stdev.	Median	Female	Male
Pre-Installation	29	93	55.8	17.1	53.5	39.5	60.5
Post-Installation	27	88	57.1	17.1	58.5	48.8	51.2

TABLE 7.4
Statistics of Respondent Age and Gender by Area in Post-Installation Survey

Area	Age (years)					Gender (%)	
	Min.	Max.	Mean	Stdev.	Median	Female	Male
NSA2 and NSA3	27	81	53	16.2	52	40.0	60.0
NSA1	30	88	61	17.3	63	57.1	42.9

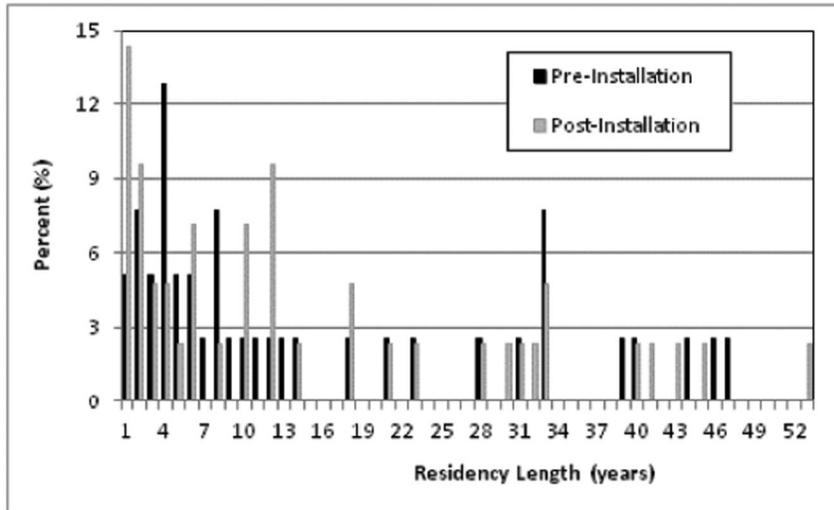


Figure 7.4 Distributions of respondents' length of residency.

TABLE 7.5
Statistical Summary of Respondents' Length of Residency

Statistics	Pre-Installation Survey		Post-Installation Survey	
	Own	Rental	Own	Rental
Min. (months)	12	1	6	3
Max. (years)	46	7	53	9
Mean (years)	20.6	2.8	20.1	2.8
Stdev. (years)	14.6	1.9	15.0	2.6
Median (years)	17	3	16	1.85

post-installation was conducted during the school summer vacation, which is probably why the response rate for the pre-installation survey is less than that for the post-installation survey. The response rate dropped by 1.9% and 4.2% for the owners- and renter-occupied

homes, respectively. Overall, the response rate for the owner-occupied homes was approximately 12% greater than that for the renter-occupied homes. This is probably due to the fact that it has been widely perceived that traffic noise has a negative impact on the value of property located close to the noise source. Consequently, the homeowners in NSA1 and NSA3 were more eager to participate in the surveys.

7.3.3 Traffic Characteristics

Traffic may cause a number of negative impacts (63), such as travel delay, congestion, noise, air pollution, health, and crashes. In the pre-installation survey, one question (Question 6) was asked about the greatest concern of the residents about these impacts. Presented in Figure 7.6 are the distributions of the responses by

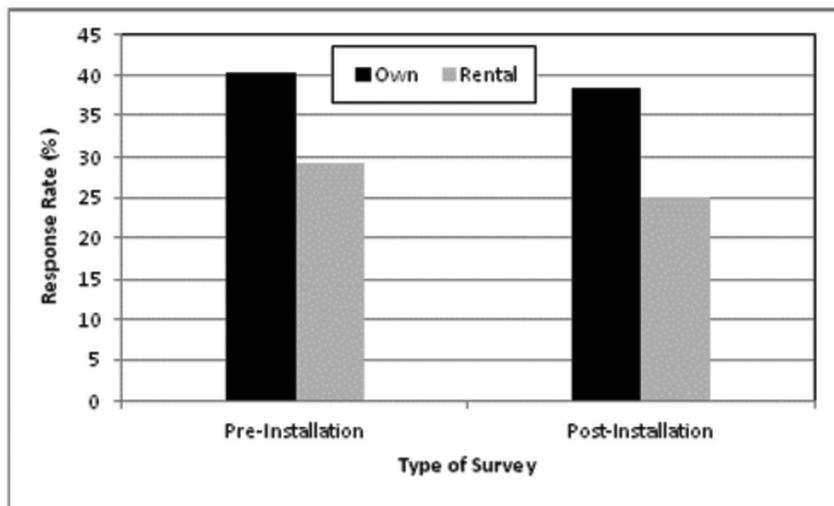


Figure 7.5 Survey response rates by type of home ownership.

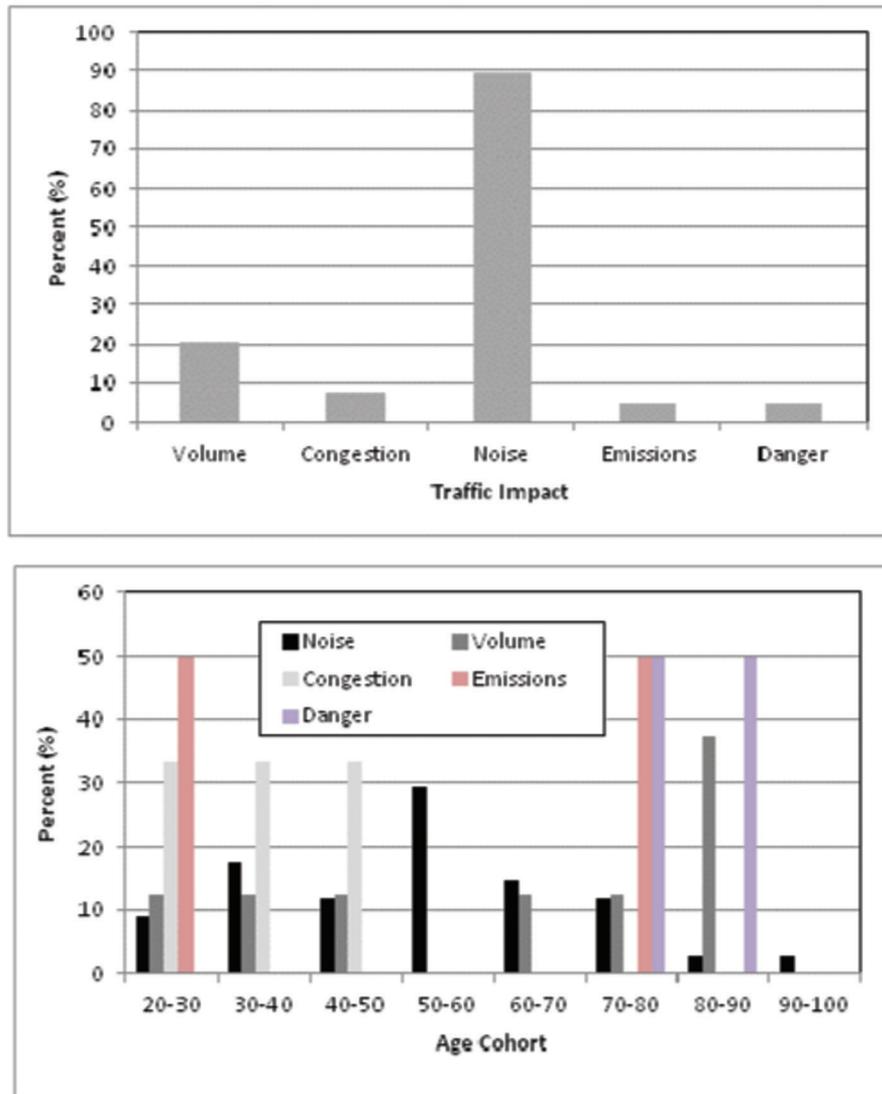


Figure 7.6 Distributions of traffic impact responses.

impact and age, respectively. Almost 90% of the respondents considered traffic noise as their greatest concern. Also, 20% of the respondents selected traffic volume and 8% of the respondents selected traffic congestion. The respondents who selected either traffic emissions or danger from vehicles accounted for 5% of all respondents, respectively. For the respondents who selected traffic noise as their greatest concern, about 29% were aged 50–60, 18% aged 30–40, and 15% aged 60–70. For the respondents with the concerns about traffic volume, 38% were in their 80 s. For the respondents with the concerns about traffic congestion, one third were in their 20 s, one third in their 30 s and one third in their 40 s. For the respondents with concerns about traffic emission, one half was aged 20–30, and one half aged 70–80. Also, all respondents with concerns about danger were aged over 70.

In the pre-installation survey, question 7 was asked about the traffic volume during the time they have lived

in their homes. Approximately, 62% of the respondents perceived a significant increase, 20% perceived a moderate increase, 18% did not perceive any change, and no respondent perceived a decrease (see top graph in Figure 7.7). It is also shown that at the bottom graph in Figure 7.7, the longer the residency, the greater increase in traffic volume. About 75% of the respondents perceiving a moderate increase and 100% of the respondents perceiving no increase had all lived for less than 5 years in the neighborhood. For the truck traffic, similar responses were received as shown in Figure 7.8. About 55.3% of the respondents perceived a significant increase, 21.0% perceived a moderate change, and 23.7% perceived no change.

However, the different responses to the truck traffic were received in the post-installation survey (see Figure 7.8). Overall, 87.1% of the respondents perceived either no change or a decrease, and 12.9% perceived an increase in truck traffic. Apparently, the

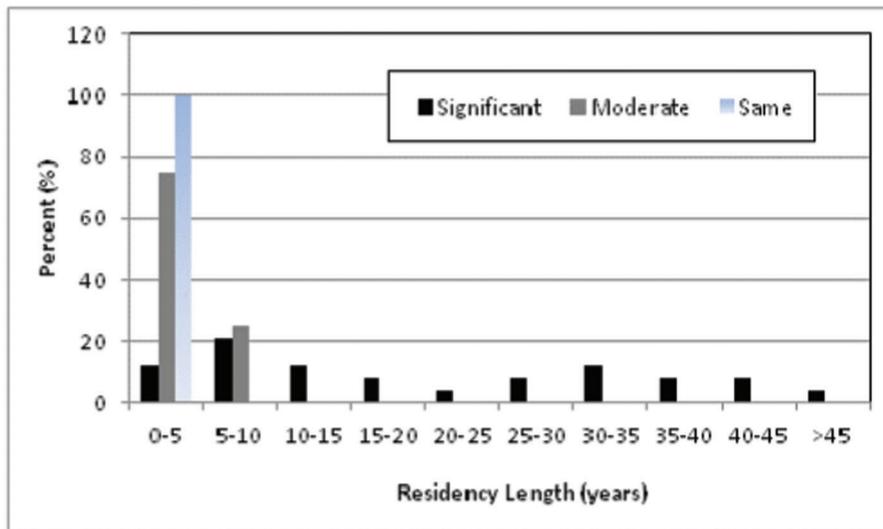
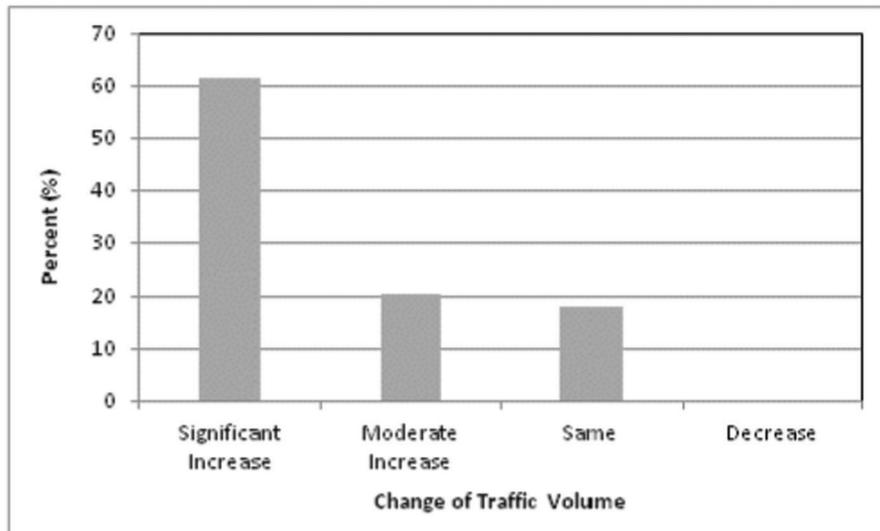


Figure 7.7 Distribution of traffic volume responses.

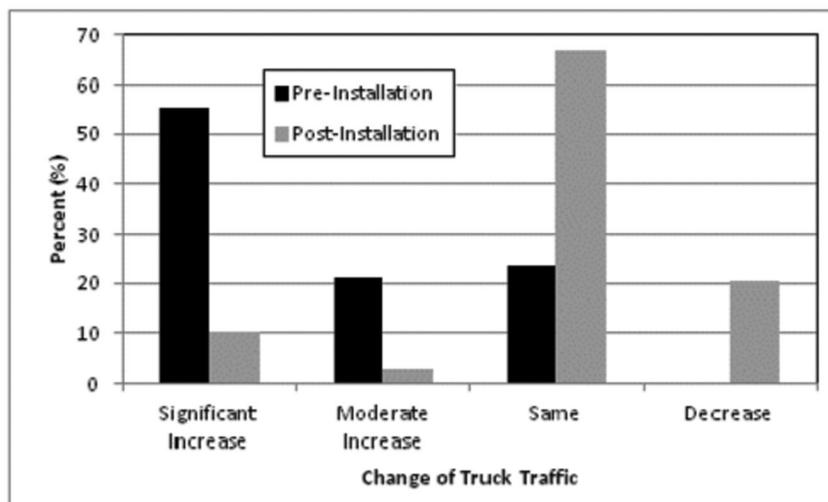


Figure 7.8 Distribution of truck traffic responses by survey time.

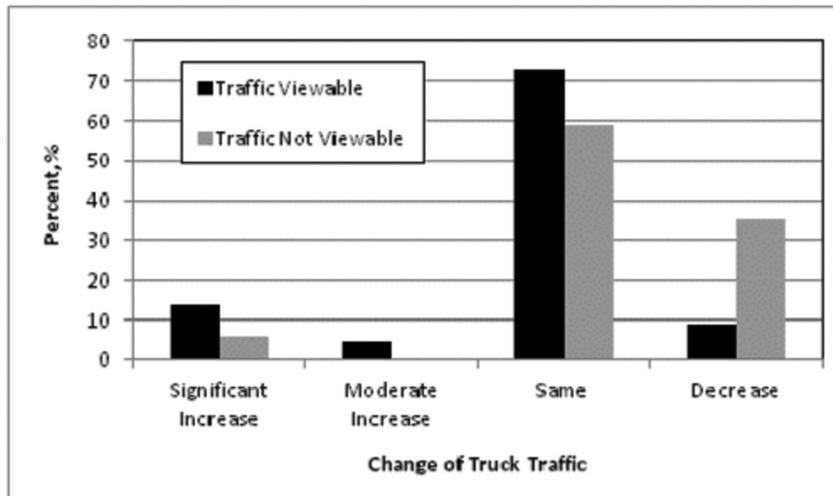


Figure 7.9 Distribution of truck traffic responses by view of traffic.

installation of noise walls produced positive perceptions about the change of traffic truck. In the post-installation survey, question 15 was asked to identify if the respondent could view the traffic above the noise walls. About 57.5% of the respondents could view traffic above the noise walls. For these respondents who could view traffic, 90.9% were located in NSA1 with LOS walls. Figure 7.9 shows the distribution of responses to truck traffic based on if traffic was viewable. For the respondents who could not view traffic, 58.8% perceived no change, 35.3% perceived a decrease and 5.9% perceived an increase in truck traffic. For the respondents who could view traffic, 72.7% perceived no change, 18.2% perceived an increase, and 9.1% perceived no change in truck traffic. It was also found that about 84.2% of the respondents, who lived in NSA1 and could view the traffic, perceived either no change or a decrease in truck traffic. Also, 93.3% of the respondents, who lived in NSA2 and NSA3 and could not view the traffic, perceived either no change or a decrease in truck traffic. The above indicates that blocking the view of traffic may provide some psychological relief to the residents.

7.3.4 Pre- and Post-Installation Noise Levels

When asked in the pre-installation survey about the change in traffic noise level from I-465 during the time the respondents have lived in their homes, 71.0% of the respondents perceived a significant increase, 13.2% perceived a moderate increase, and 15.8% perceived no change, as shown on the top of Figure 7.10. Further analysis indicated that the responses were independent of the respondent's age and gender, but varied with the length of residency. As shown at the bottom of Figure 7.10, the longer the residency the greater the increase in traffic noise perceived. All respondents perceiving no change and 60.0% of the respondents perceiving a moderate increase had lived in their current

homes for not more than 5 years. The above indicates that the increase of traffic noise occurred gradually and slowly in the project area.

In response to the question about the pre-installation noise level, 70.3% of the respondents rated the noise level very loud, 27.0% rated the noise level loud, and 2.7% rated the noise level no problem (see Figure 7.11). When asked about the post-installation noise level, however, 26.2% of the respondents rated the noise level every loud, 52.4% of the respondents rated the noise level loud, and 21.4% of the respondents rated the noise level no problem. Between the pre- and post-installation surveys, the percentage of respondents perceiving very loud noise decreased by up to 44.1%. Nevertheless, the percentage of respondents rating noise level no problem increased by 18.7%. It was also interesting to note that difference between the two percentages for very loud noise is exactly the sum of the two differences for both loud noise and no problem noise. It is obvious that the respondents in the project area received a perceivable noise reduction after the installation of the noise walls.

The authors further examined the possible factors that might have affected the responses to the post-installation noise level. As shown at the top of Figure 7.12, the respondents from NSA1 with LOS walls provided more negative perception than the respondents from both NSA2 and NSA3 with conventional noise walls. The percentage of the respondents rating the noise level very loud increased from 20.0% in NSA1 to 31.8% in NSA2 and NSA3, and the percentage of the respondents rating the noise level loud increased from 45.0% in NSA1 to 59.1% in NSA2 and NSA3. However, the respondents rating the noise level no problem decreased from 35.0% in NSA1 to 9.1% in NSA2 and NSA3. This implies that the greater noise reduction was perceived by the respondents in NSA2 and NSA3 than those in NSA1. For the respondents who could view the traffic shown at the bottom of Figure 7.12, 39.1% rated the noise level very

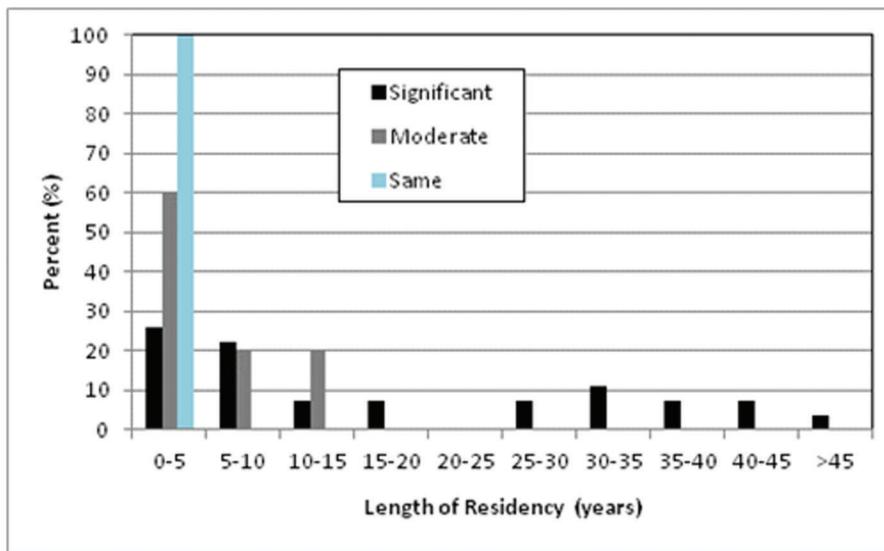
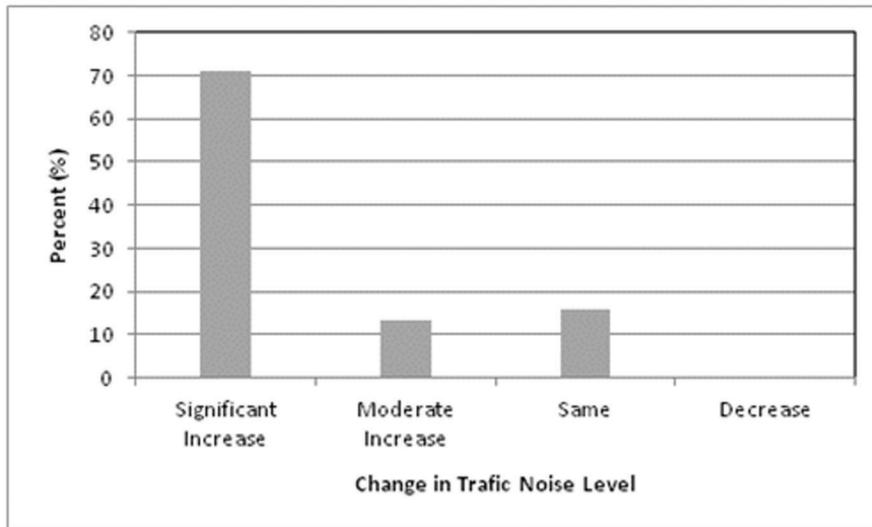


Figure 7.10 Distributions of noise change responses.

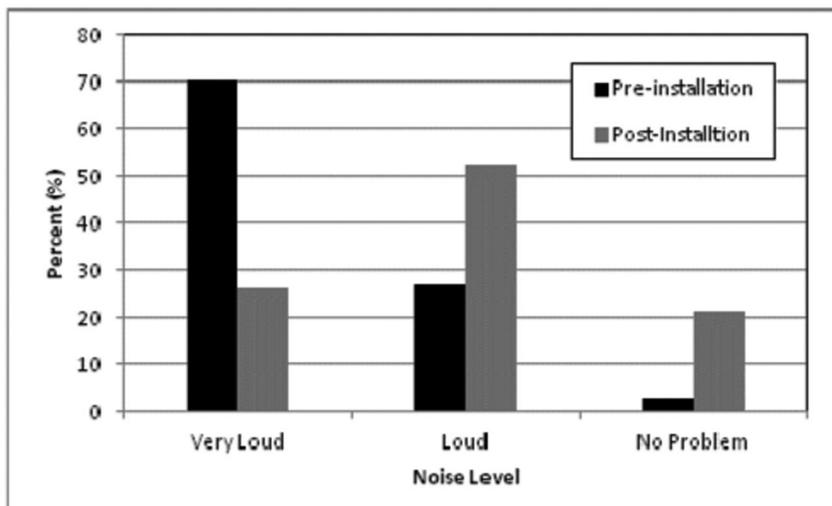


Figure 7.11 Distributions of noise level responses by survey time.

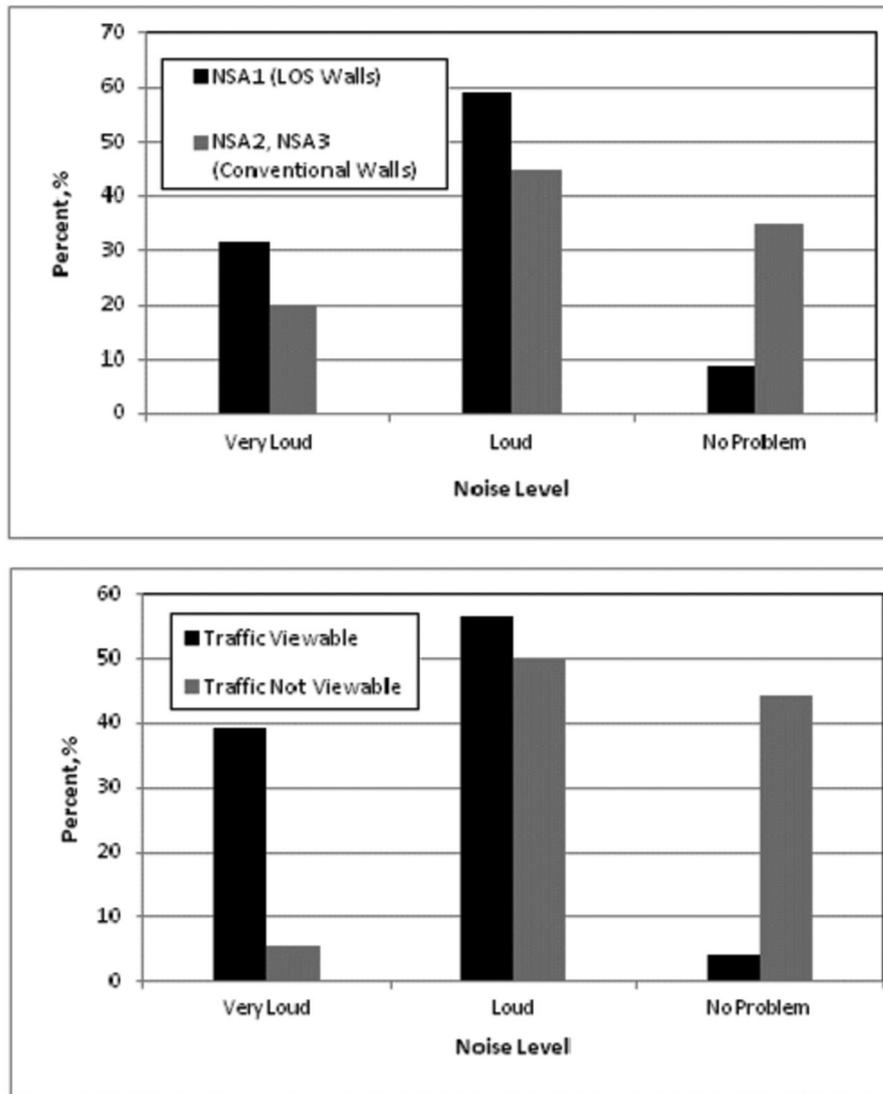


Figure 7.12 Distributions of noise level responses by area and view of traffic.

loud and 56.5% rated the noise level loud. For the respondents who could not view the traffic, 5.6% rated the noise level very loud and 44.4% rated the noise level no problem. The above indicates that the view of traffic above the noise wall may also play an important part in respondents' perception of the post-installation noise level.

In the pre-installation survey, questions (questions 15 and 16) were also asked to identify what day (see top graph in Figure 7.13) and when (see bottom graph in Figure 7.13) the greatest noise impact occurred, respectively. About 56.4% of the respondents perceived noticeable noise day to day and 38.5% of the respondents perceived noticeable noise on weekdays. Only 10.3% of the respondents perceived noticeable noise on weekends. No respondents perceived noticeable noise on holidays. Also, 53.8% of the respondents indicated that noticeable noise occurred during 3 pm-

6 pm and 6 pm-10 pm, respectively. Seemingly, the noise level was more noticeable during daytime, particularly during the after-school time. The above was utilized to determine the time for field noise testing and agreed well with the test results presented in Chapter 4.

7.3.5 Pre- and Post-Installation Noise Impacts

Figure 7.14 shows the distributions of responses to the questions of how the traffic noise from I-465 affects the respondents' life quality before and after the installation of the noise walls, respectively. The percentage of the respondents rating the noise impact very negative decreased from 35.1% in the pre-installation survey to 19.0% in the post-installation survey. Also, the percentage of the respondents rating the noise impact negative decreased from 56.8% in the

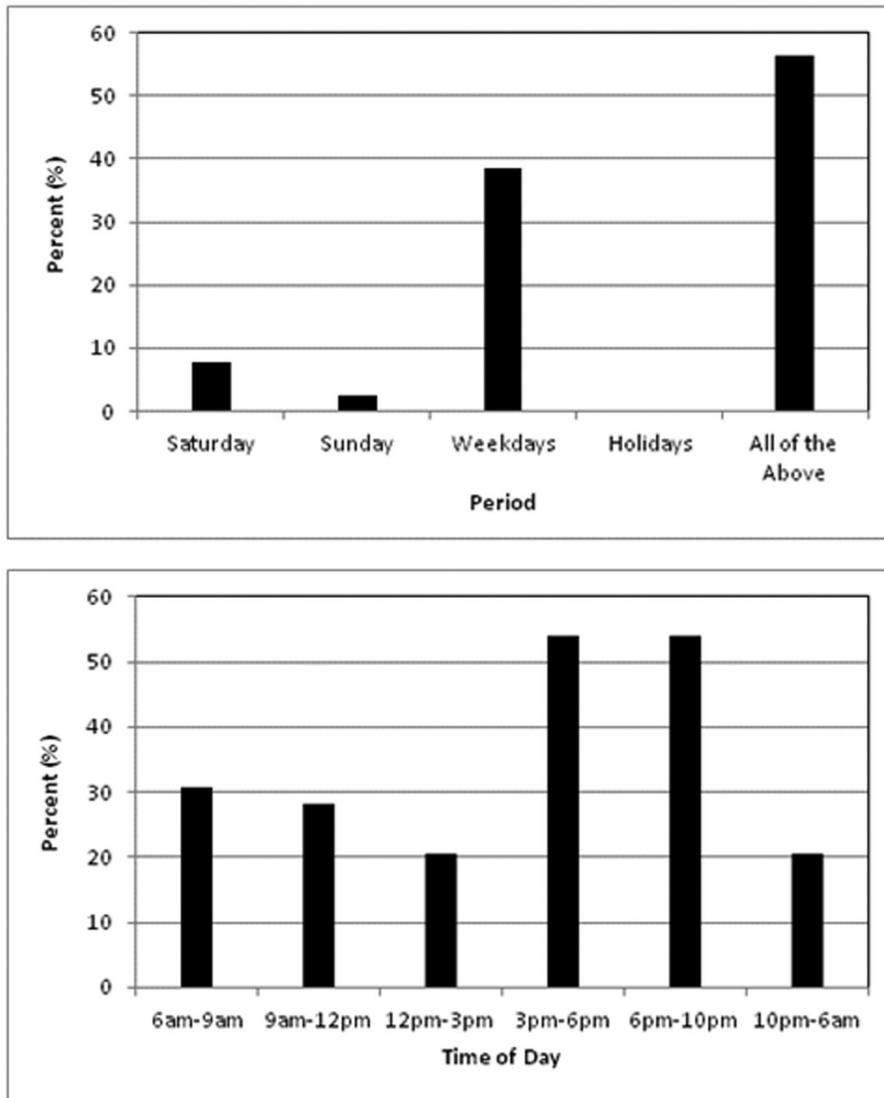


Figure 7.13 Distribution of noise level responses by time and day.

pre-installation survey to 45.2% in the post-installation survey. However, the percentage of the respondents perceiving no impact increased from 8.1% in the pre-installation survey to 35.7%. Apparently, the noise walls significantly mitigated the impacts of traffic noise from I-465 on the respondents' life quality.

As shown in Figure 7.15 are the distributions of the responses to the impact of traffic noise on the respondents' life quality by area and by view of traffic, respectively. The respondents in NSA1 perceived severer noise impact on their life quality than the respondents in both NSA2 and NSA3 (see top graph in Figure 7.15). In NSA1 after installing the LOS walls, only 13.6% of the respondents perceived no impact. However, 60.0% of the respondents perceived no impact from noise after installing the conventional noise walls in both NSA2 and NSA3. Again, the

responses depended to some extent on if the respondents could view the traffic above the walls. For the respondents who could view the traffic, a total of 91.3% perceived either very negative or negative noise impact. For the respondents who could not view the traffic, only 30.0% perceived either very negative or negative noise impact.

Figure 7.16 shows the distributions of the responses to questions about the impact of traffic noise from I-465 on the respondents' indoor and outdoor activities. It can be seen that from the shapes of the two plots, there was a shift in the response patterns between the pre- and post- installation surveys. For the pre-installation survey (top), the surface plot peaks occur at the left and right boundaries, particularly at the impact, "All the Time" on the activities, such as "Window Open" (Ability Keep Window Open) and

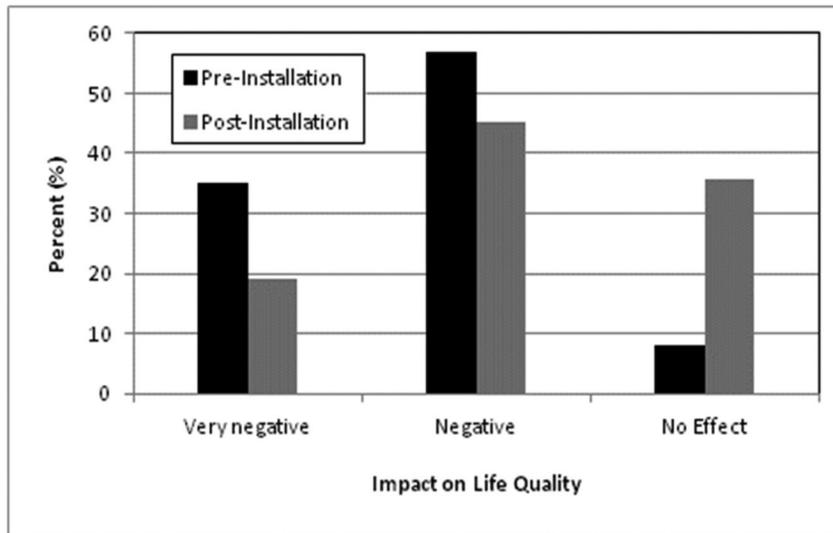


Figure 7.14 Distributions of noise impact responses by survey time.

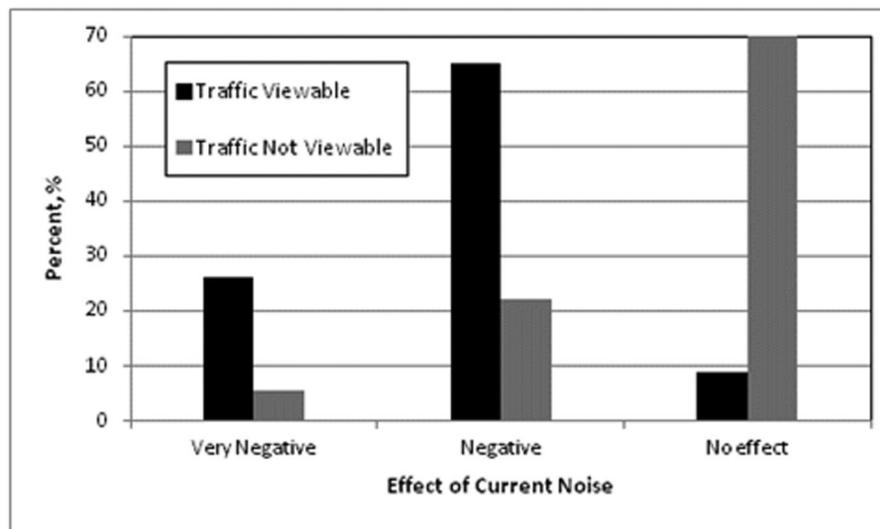
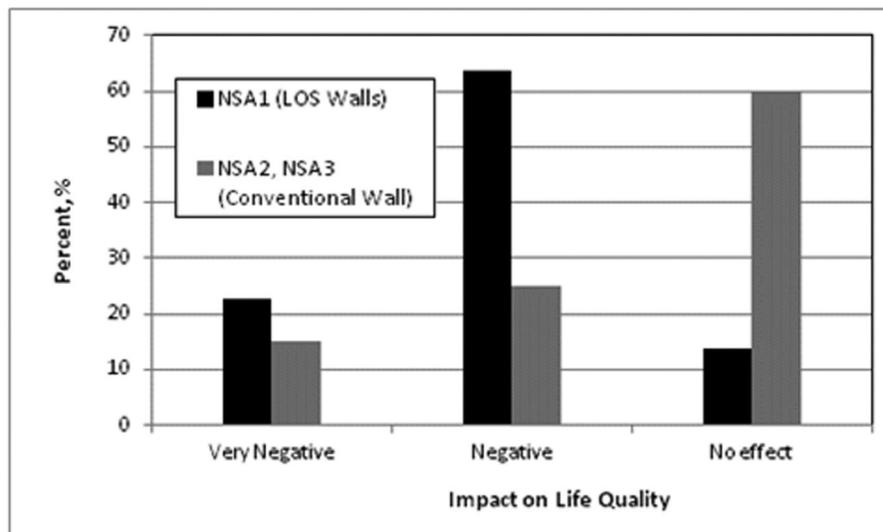


Figure 7.15 Distributions of noise impact responses by area and view of traffic.

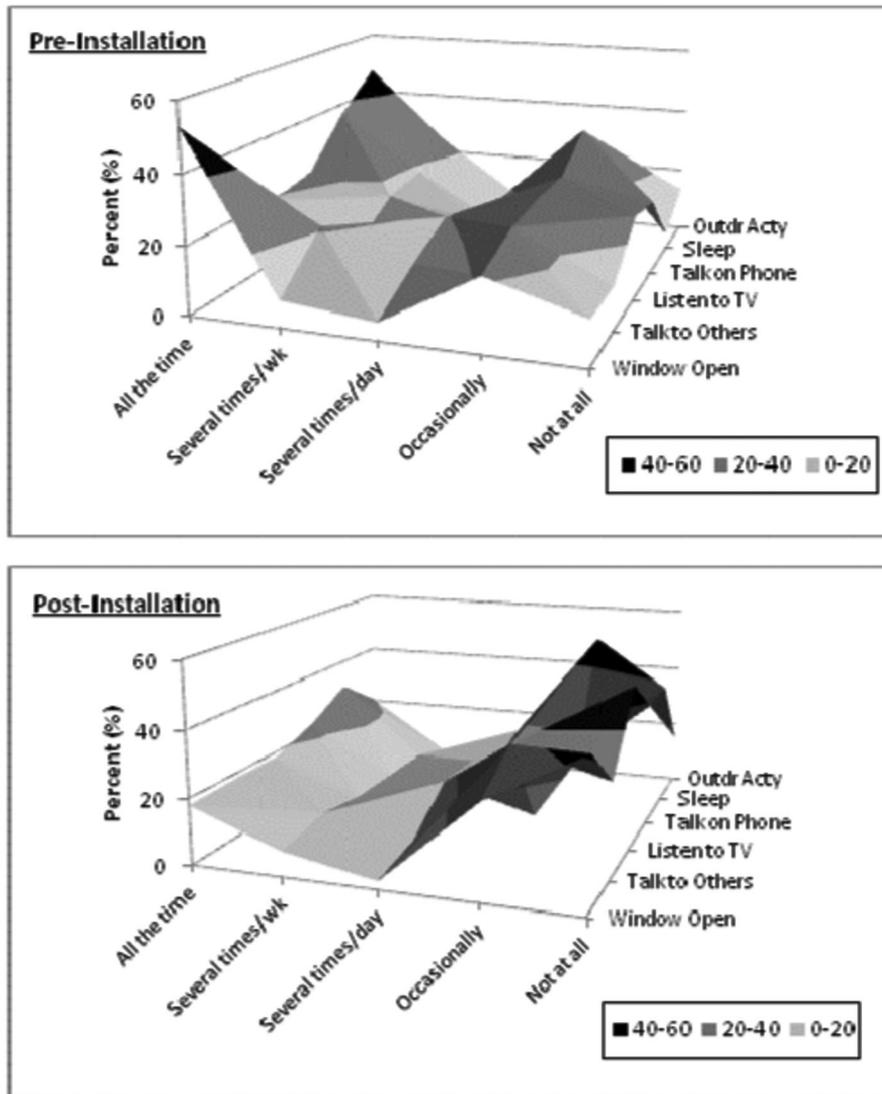


Figure 7.16 Responses to noise impact on respondents' activities.

“Outdr Acty” (Outdoor Activities). The largest percent is 56.2% which occurred to all the time impact on the ability to keep the window open. The responses are distributed relatively evenly in the middle of the plot. For the post-installation survey (bottom), the surface plot peaks mainly at the right boundary, particularly at the impact, “Occasionally” on the activity, “Outdr Acty” (Outdoor Activities). The responses are distributed relatively evenly in the other parts, particularly the left parts. The largest percent, 43.6% occurred to the occasional impact on outdoor activities. Obviously, the impacts of traffic noise on the respondents' activities decreased after installing the noise walls.

Figure 7.17 shows the distributions of responses to traffic noise impacts during daytime and nighttime, respectively. The noise impact was greater during nighttime than during daytime before installing the noise walls. However, the noise impact was less during

nighttime than during daytime after installing the noise walls. Apparently, the noise impact decreased during both daytime and nighttime after installing the noise walls, particularly during nighttime. Figure 7.18 shows the distributions of the responses from NSA1 after installing the LOS walls. More respondents perceived noise impact during daytime than during nighttime. Notice that the respondents perceived noise impact during daytime in NSA1 could commonly view the traffic above the LOS walls. Again, no effects of the respondents' age and gender were identified.

Questions were also asked in the pre- and post-installation surveys to identify the potential effects of traffic noise and noise walls on the frequency and pattern of family plays in the respondents' yards. Figure 7.19 shows the distributions of the responses in the pre- and post-installation surveys, respectively. One lesson learned from this is that the question in the pre-

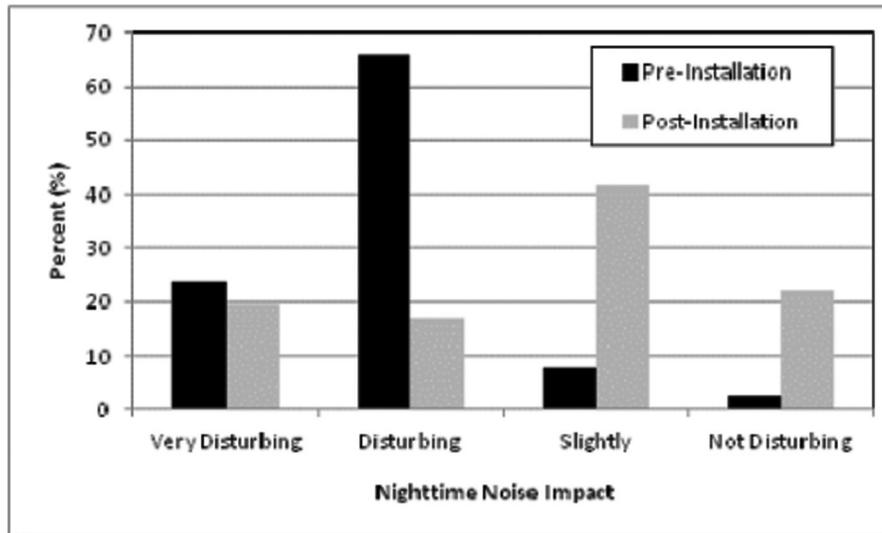
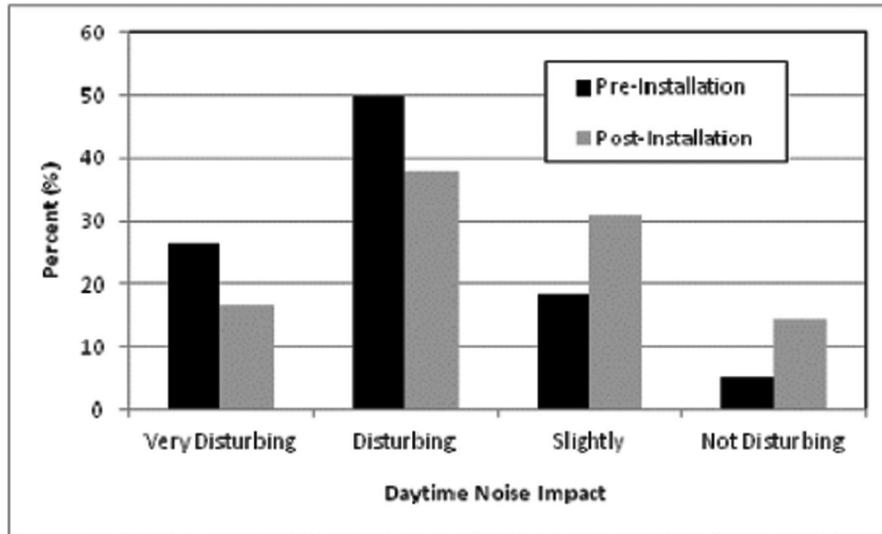


Figure 7.17 Distributions of noise impact responses during daytime and nighttime.

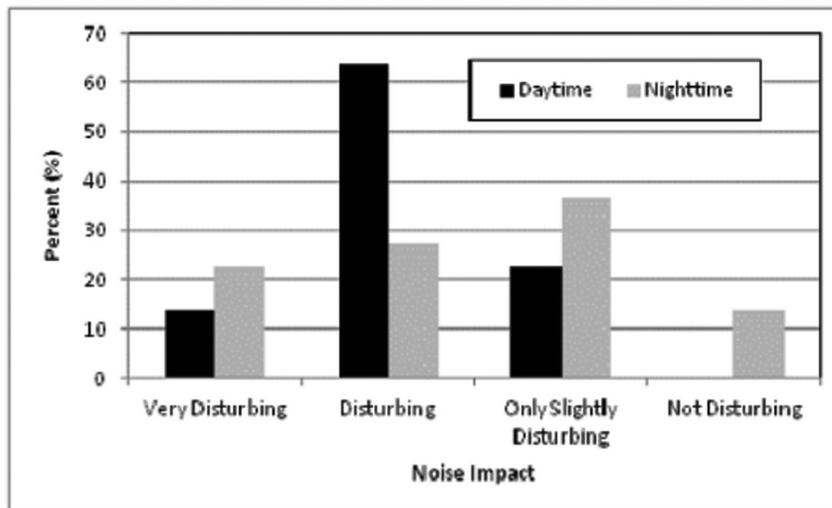


Figure 7.18 Distributions of noise impact responses in NSA1 after installing LOS walls.

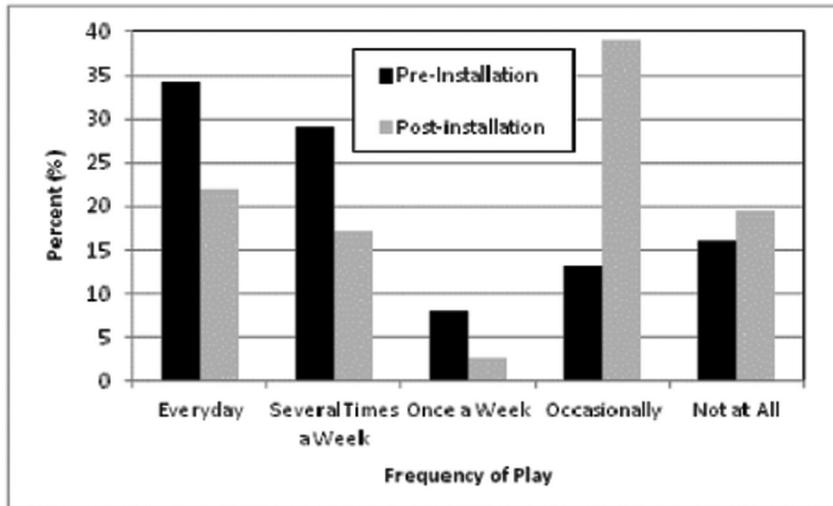


Figure 7.19 Distribution of noise impact responses by day.

installation survey did not specify the time and might cause some confusion. As a result, some respondents selected the answer for the time before the construction of I-465 expansion and others for the time after the construction of I-465 expansion. In reality, several residents indicated that to us during field noise testing, the installation of noise walls improved both safety and security for kids playing in their backyards.

7.3.6 Features of Noise Walls

Presented in Figure 7.20 are the distributions of the responses to the question, i.e., Question 14 in the post-installation survey about the respondents' opinions on the appearance the noise walls. In NSA1 with the LOS walls, about half of the respondents were either very displeased or somewhat displeased with appearance of

the LOS walls. In NSA2 and NSA3 with the conventional noise wall, 52.6% of the respondents were either very pleased or somewhat pleased with appearance of the conventional noise wall, and only 10.5% of the respondents were either very displeased or somewhat displeased with appearance of the conventional noise wall. It was noticed that in NSA1, 90.9% of the respondents displeased with the appearance of the LOS walls were living on either North Temple or Haverstick Avenue. Further examination of the responses revealed that for these respondents who were both displeased with the appearance of the LOS walls and living on either North Temple or Haverstick Avenue, 70% responded that the LOS walls should be either higher or longer.

The waviness occurred in the outer skin on the Noise D-Fence wall might also play an important part

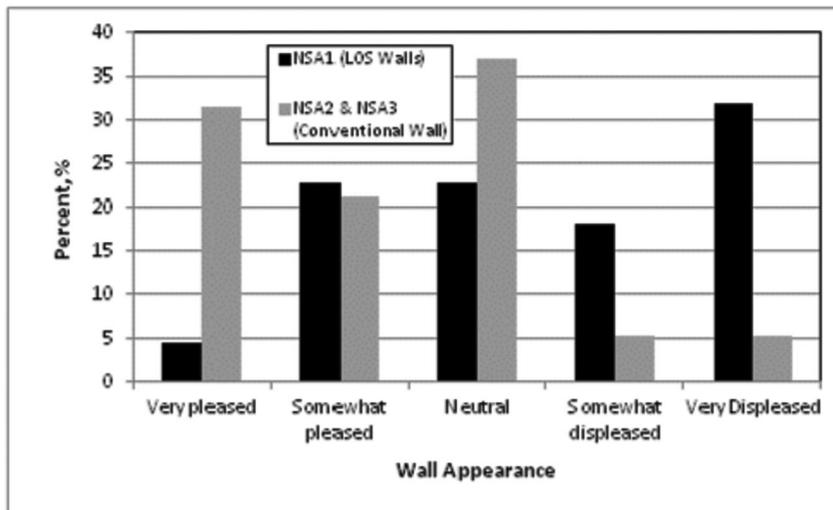


Figure 7.20 Distributions of noise wall appearance responses.

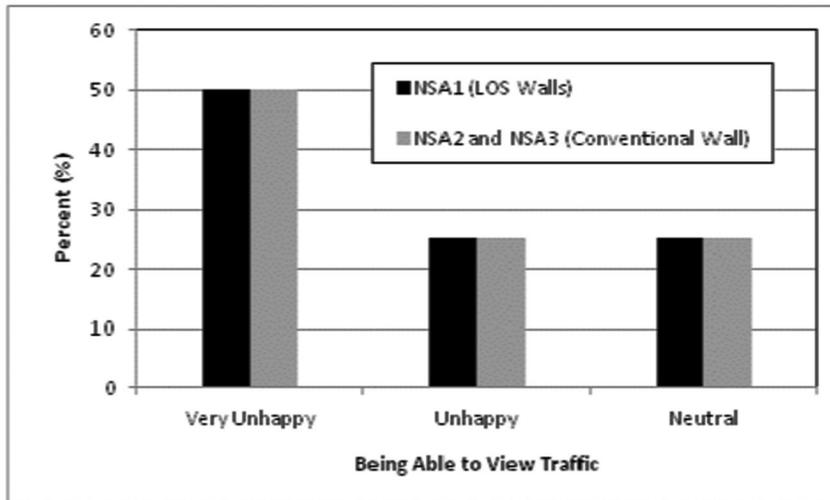


Figure 7.21 Distributions of noise wall appearance responses.

in the respondents' perceptions of the appearance of the LOS walls. Actually in response to the open-ended question (Question 19) in the post-installation survey, several respondents indicated their concerns about this. In addition, the conventional noise walls in NSA2 and NSA3 just across I-465 were engineered to achieve a substantial noise reduction of at least 7 dBA, and therefore much higher and longer than the LOS walls. Consequently, the respondents in NSA1 tended to compare the LOS walls to the conventional noise walls and were simply anticipating a noise wall the same as the conventional noise wall. It has also been mentioned constantly in the previous sections, whether the respondents could view traffic above the noise walls did affect their perceptions of the noise levels. When asked about the respondents' feelings about being able to see traffic above the noise walls,

the distribution of the responses from NSA1 with the LOS walls followed the same trend as that from NSA2 and NSA3 (see Figure 7.21). This implies that the feeling about being able to see traffic was independent of the type of noise wall. About 75% of the respondents felt unhappy about viewing traffic above the noise walls.

7.3.7 Noise Regulation and Policy

In response to questions about the respondents' familiarity with federal noise regulations and INDOT noise policy (see Figure 7.22), about 82.1% of the respondents indicated that they either had limited familiarity or were not familiar at all with the federal noise regulations and 81.1% of the respondents indicated that they either had limited famil-

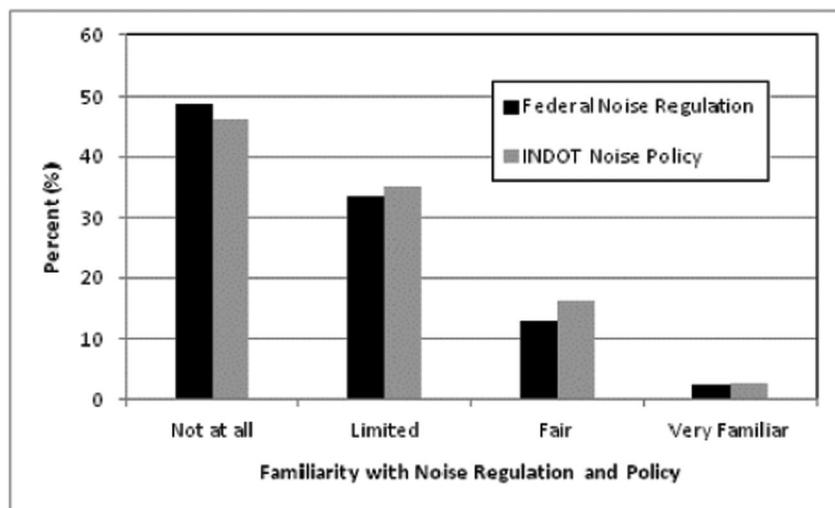


Figure 7.22 Respondents' familiarities with noise regulations.

ilarity or were not familiar at all with INDOT noise policy. It was also noticed that 71.1% of the respondents either had limited familiarity or were not familiar at all with traffic noise reduction measures. The above may imply that INDOT should further step up its outreach activities to promote public awareness of both federal regulation and agency's policy and understanding of the agency's efforts made to abate traffic noise. In addition, the survey results showed that 70.3% of the respondents had never complained to the agency about the traffic noise in their neighborhoods.

The respondents were also asked for their opinions about the cost-effectiveness and contribution for noise reduction measures (see Figure 7.23). In response to the question, if the noise wall could be built when the cost-effectiveness of \$25,000 per benefited receptor is exceeded, 65.8% of the respondents indicated that noise

walls should be built even if they are not cost effective and 18.4% would accept a cheap alternative to provide some noise reduction (left). When asked about their willingness to contribute money if the \$25,000 per benefited receptor is exceeded, 81.6% of the respondents answered No and 18.4% answered yes (middle). Of those respondents willing to contribute money, 14.3% indicated that they would contribute only after considering other special exceptions. The remaining respondents were equally split among \$1,000, \$1,000–\$3,000 and \$3,000–\$5,000 (right). The respondents were further asked whether alternative walls with limited noise reduction should be built when the \$25,000 per benefited receptor is exceeded (see Figure 7.24). About 54.3% of the respondents answered yes and 45.7% answered no (left). When asked if it was worth the money to build, 66.7% of the respondents in NSA2 or NSA3 answered yes and 33.3% answered no to the



Figure 7.23 Responses to noise wall cost-effectiveness and contributions.

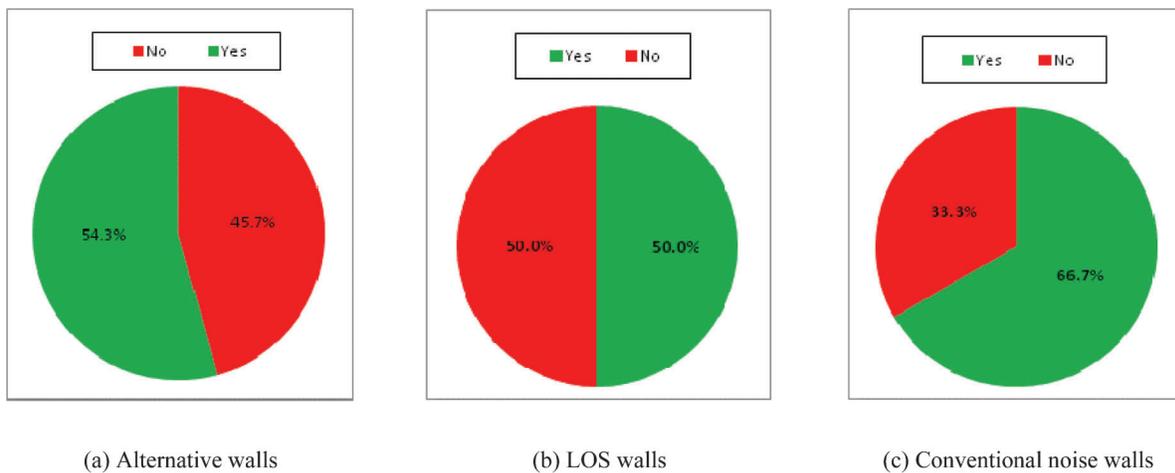


Figure 7.24 Responses to alternatives and cost-worthiness of noise walls.

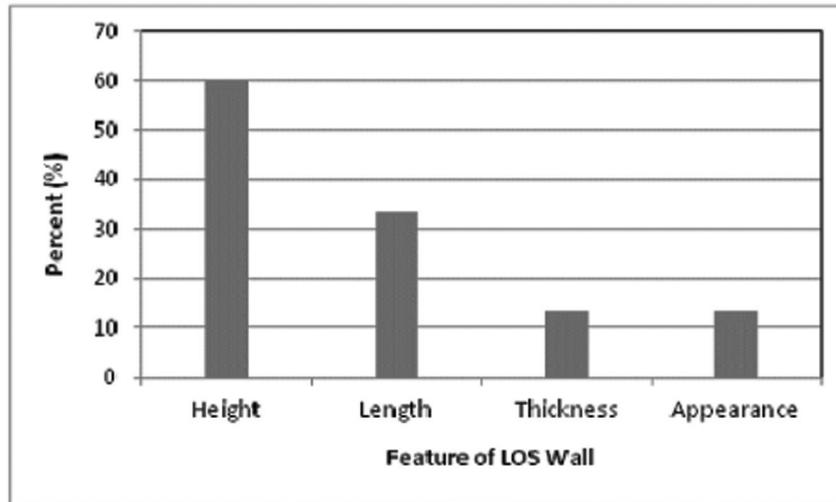


Figure 7.25 Distribution of responses to noise wall features.

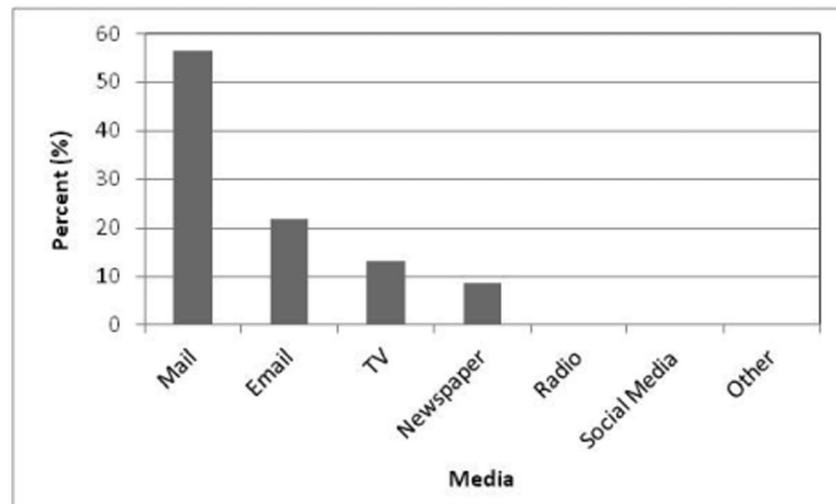


Figure 7.26 Distribution of responses to media type.

conventional noise walls (middle). In NSA1, the respondents were equally split between yes and no to the LOS walls (right).

The respondents also offered additional comments regarding the noise walls constructed. In NSA1, 60.0% of the respondents indicated that the LOS walls are too low, 33.3% too short and 13.3% too thin (see Figure 7.25). Also, 13.3% of the respondents indicated the waviness on the Noise D-Fence wall. Finally, the respondents were asked how they would prefer to receive information on public involvement in traffic noise. The majority (56.5%) of the respondents would prefer to receive the information by mail, 21.7% by email, 13.0% by TV, and 8.7 by newspaper (Figure 7.26). Surprisingly, however, no respondent would prefer to receive the information by any type of social media, such as Facebook and Twitter. The authors further broke down the responses by respondent's age and gender. No trend or pattern was identified.

8. FINDINGS AND RECOMMENDATIONS

8.1 Main Findings

8.1.1 State DOT Traffic Noise Policies

Fourteen state DOTs opt to participate in Type II projects. In the Midwest, Illinois, Michigan and Ohio have participated in Type II projects. Wisconsin has established the WisDOT Retrofit Noise Barrier Program that consists of a list of state-funded, stand-alone noise abatement projects on existing highways. INDOT currently does not participate in Type II projects.

Eighteen state DOTs define a substantial noise increase of 10 dBA and twenty-three state DOTs define a substantial noise increase of 15 dBA. In the Midwest, a substantial noise increase of 15 dBA is employed by Indiana and Wisconsin, 10 dBA by Kentucky, Michigan and Ohio, and 14 dBA by Illinois.

Nineteen state DOTs have established a maximum height of 14 ft. to 30 ft. for noise walls. A maximum height of 20 ft., 25 ft. and 30 ft. is defined by 37%, 26% and 16% of the state DOTs, respectively. In the Midwest, Ohio defines a maximum noise wall height of 25 ft. and the others do not have a specific maximum wall height limitation.

Forty-nine state DOTs consider a noise abatement to be acoustically feasible if a noise reduction of at least 5 dBA is achieved at the impacted receptors. One state DOT requires a minimum of 9 dBA reduction for at least one impacted receiver. There are two methods for defining the number of impacted receptors used to assess the acoustic feasibility. In the first method currently used by thirty state DOTs, a minimum noise reduction is required for at least 1 impacted receptors by nine state DOTs, for the majority (50%+1) of all impacted receptors by seven state DOTs (including INDOT), and for at least 50% of all impacted receptors by five state DOTs. In the second method currently used by sixteen state DOTs, a minimum noise reduction is required at 50%+1 of the impacted receptors in the front row by four state DOTs, at 75% or more of the impacted receptors in the front row by three state DOTs, and at 50% or more of the impacted receptors in the front row by two state DOTs.

A noise reduction of at least 5 dBA is required for at least 1 impacted receptors by nine state DOTs, for the majority (50%+1) of all impacted receptors by 7 state DOTs (including INDOT), and for at least 50% of all impacted receptors by 5 state DOTs. The second method currently used by sixteen state DOTs is to define a specific number out of the impacted receptors in the front row. A noise reduction of at least 5 dBA is required at 50%+1 of the impacted receptors in the front row by four state DOTs, at 75% or more of the impacted receptors in the front row by three state DOTs, and at 50% or more of the impacted receptors in the front row by two state DOTs. Three state DOTs require a noise reduction of at least 5 dBA without specifying the number of impacted receptors.

The cost-effectiveness can be calculated using either the actual construction cost or cost per square foot or the maximum square footage per benefited receptor. Forty-three state DOTs (including INDOT) use the allowable cost per benefited receptor, which varies between \$20,000 and \$60,000 with an average of \$35,227 per benefited receptor. Eleven state DOTs define an allowable cost of \$20,000–\$25,000 per benefited receptor and thirty-two state DOTs define an allowable cost of more than \$25,000 per benefited receptor. The allowable costs for other Midwest state DOTs vary between \$30,000 and \$42,500 with an average of \$34,600 per benefited receptor. The current allowable cost is \$25,000 per benefited receptor for INDOT and is the same allowable cost in 2007. Seven state DOTs utilize the maximum square footage per benefited receptor to measure the cost-effectiveness. The maximum square footage varies between 1000 ft² and 2700 ft² per benefited receptor. No state DOTs in

the Midwest use the maximum square footage per benefited receptor currently.

The new FHWA noise regulation mandates a noise reduction design goal between 7 dBA and 10 dBA at benefited receptors. Thirty-six state DOTs define a noise reduction design goal of 7 dBA and seven state DOTs define a noise reduction design goal of 10 dBA. In the Midwest, Indiana, Kentucky, Michigan and Ohio define 7 dBA as the noise reduction design goal. The noise reduction design goal is 8 dBA for Illinois and 9 dBA for Wisconsin.

FHWA does not allow use of the third party funding to supplement the cost of noise abatement on Type I Federal-aid projects unless the abatement measure is determined to be feasible and reasonable without the supplemental. Third party funding can only be used to pay for additional features, including landscaping, aesthetic treatments, and functional enhancements (sound-absorbing treatment), and access doors. Several state DOTs allow the use of third party funding in some special situations. Third party funding is mainly used to construct noise abatement measures within the State right-of-way. Third party funding is mainly used to construct noise abatement measures for retrofit projects. In cases where abatement is not eligible for federal-aid funding, and other groups, including local government and residents, insist on providing a noise abatement measure, other groups must assume 100% of all costs, including pre-engineering cost, construction cost, and maintenance cost under an agreement signed by the state DOT and the local municipality acting for other groups.

8.1.2 Construction, Cost, and Structural Evaluation

Metal walls are vulnerable to the impacts of rocks and errant vehicles and require protection guardrails. Wood walls are prone to weathering, resulting in gaps and therefore reduced acoustic performance. The fiberglass noise walls may cost as much as the precast concrete wall. The acrylic noise walls may cost two times as expensive as the precast concrete wall to achieve a same noise reduction. The vegetation noise walls may not be UV-stable and the maintenance, particularly watering to keep the plants alive, is costly.

The construction cost of the precast concrete noise wall was close to that of the CMU block noise wall. The amount of work of the noise wall may affect the unit construction cost significantly. The larger the amount of work the lower the unit construction cost. The unit construction cost of precast concrete noise walls falls within a range of \$32.6/ft² to \$35.1/ft² at a confidence level of 95% in the past. The regional cost differences of the construction of noise walls are not evident within the State. While the construction costs of noise walls have experienced fluctuations over the past two decades, overall it demonstrates an increasing tendency with time.

The construction cost of noise wall is commonly broken down to three pay items by INDOT, including

barrier design and layout, barrier panels, and panel erection. For the conventional Durisol precast concrete noise wall, the three pay items accounted for 2.8%, 75.8%, and 21.4% of the total cost, respectively. For the LOS walls, the three pay items shared on average 10.1%, 62.9%, and 27.0% of the total construction cost, respectively. The unit cost for LOS walls was \$30/ft², which is much more than for the Durisol precast concrete wall (\$23.4/ft²). This is because the competitive bids for the LOS walls were not available due to the small amount of the work and because the foundation for the Durisol precast concrete wall was utilized for the LOS walls.

All these four noise walls demonstrated satisfactory surface conditions in terms of integrity and color right after construction. No chipping, spalling, cracking and color fading, were observed. However, waviness was observed in the outer skin on one portion of the Noise D-Fence wall. Ground penetration radar (GPR) testing was conducted right after construction to evaluate the initial structural integrity of these noise walls. It was found that at this time, each panel has consistent dielectric properties in the horizontal and thickness directions, respectively.

8.1.3 Pre- and Post-installation Noise Levels

The hourly noise variation followed a trend similar to the hourly traffic variation. The maximum hourly noise variation was 2 dBA. The greatest noise level occurred approximately at 8 am. The noise levels on weekends were much less than those on weekdays. The maximum weekly noise difference was 1.2 dBA over the weekdays. There should be no noticeable differences in the noise measurements regardless of the time of day and day of week (weekdays) in the study areas.

In NSA1 (LOS walls, Temple Ave.), the pre-installation noise levels at all 23 homes varied from 55.5 dBA to 71.7 dBA with an average of 65.0 dBA. The post-installation noise levels dropped to 50.6-67.0 dBA with an average of 60.2 dBA. The noise reduction varied between 2.5 dBA and 12.2 dBA with an average of 4.8 dBA. Also, 63.6% of the impacted homes received a noise reduction ≥ 5 dBA, which indicates that the LOS walls are acoustically feasible.

In NSA2 (conventional Durisol noise wall, Retreat Apt), the pre-installation noise levels ranged between 63.2 dBA and 73.2 dBA with an average of 68.2 dBA. The post-installation noise levels varied between 57.8 dBA and 65.6 dBA with an average of 62.0 dBA. The noise reduction varied from 3.3 dBA to 7.9 dBA with an average of 6.1 dBA. For the impacted homes, 75.0% received a noise reduction ≥ 5 dBA. This confirms that the conventional Durisol noise walls are acoustically feasible in NSA2.

In NSA3 (conventional Durisol noise walls, East 101 St.), the pre-installation noise levels ranged between 60.5 dBA and 69.9 dBA with an average of 65.5 dBA. The post-installation noise levels varied between 58.0 dBA and 64.0 dBA with an average of 61.6 dBA. The

noise reduction varied from 3.3 dBA to 7.9 dBA with an average of 6.1 dBA. All post-installation noise measurements were below the NAC, i.e., 66 dBA.

The pre-installation noise level decreased as the distance or the elevation difference increased. The pre-installation noise level was more closely related to the elevation than the distance. After installing the noise walls, the principles of sound propagation remain valid after installing the noise walls. However, the strongest correlation arose between the post-installation noise level and distance. Also, the post-installation noise level was more closely associated with the noise wall height than the elevation difference. This may imply the effect of noise wall, particularly sound diffraction. The noise reduction not necessarily always decreases as the distance increases.

8.1.4 Psychoacoustic-based Noise Wall Effectiveness Evaluation

Psychoacoustic-based noise wall effectiveness evaluation was made through the insertion loss spectrum density and normalized annoyance. It was shown that the conventional Durisol noise wall is more effective in noise reduction. The height of Durisol noise wall could affect its noise reduction capability. The shorter the Durisol noise wall the less effective the noise reduction, especially in higher frequency bands. The LOS walls are less effective than the Durisol noise wall. However, LOS walls can reduce some noise impact. Among AAC, Noise D-Fence and Sanders Precast walls, AAC wall is less effective than Noise D-Fence and Sanders Precast walls. Based on the psychoacoustic annoyance as a measure, Sanders Precast wall can perform slightly better than Noise D-Fence wall in noise reduction.

8.1.5 Prediction and Analysis of Traffic Noise over Design Year

The performances of the constructed prediction models varied from area to area, from model to model, and from pre-installation stage to post-installation stage. The 95% confidence interval for the pre-installation model in NSA2 falls completely outside the valid range of ± 3 dBA. The 95% confidence intervals for other models fall within the valid range of ± 3 dBA. In NSA2, the distribution of noise discrepancies is strongly, positively skewed for the constructed pre-installation model. Also, the pre-installation noise discrepancies in NSA2 exhibit very poor correlation with the receiver's elevation and the distance between the receiver and the highway. Therefore, this model might involve some consistent errors and can be adjusted simply by adding 5 dBA to the predicted value.

The pre-installation noise levels predicted with DGAC, OGAC and Average pavements are respectively 2.9 dBA, 3.5 dBA and 2.0 dBA less than that with PCC. However, the noise differences due to the pavement type become less after installing the noise walls.

The noise level increases by around 5 dBA as traffic speed increases from 50 mph to 75 mph, approximately 1 dBA per 5 mph increase in traffic speed. The predicted noise levels are all below 66 dBA at 55 mph. It was found that the effect of traffic speed on the noise level is independent of the ground condition to some extent and is probably dependent on the noise prediction methodologies utilized by TNM 2.5. The effect of traffic volume on the noise level is also independent of the ground condition, which is solely due to the noise prediction methodologies used by TNM 2.5. The noise level increases by approximately 1.7 dBA from the first year to the design year regardless of the area. In other words, the traffic noise level increases by less than 0.1 dBA each year.

The predicted noise level decreases as NRC increases. However, the amount of noise reduction is completely negligible. The total amount of noise reduction is 0.2 dBA when the NRC increases from 0 to 0.95. This indicates that the Durisol, AAC, Noise D-Fence and Sanders noise walls may provide similar acoustic performance to the protected side.

As the noise wall height increases from 10 ft. to 24 ft., the noise level decreases by about 5.6 dBA regardless of the study area. However, the decrease rate drops as the noise wall height increases, particularly when the noise wall exceeds 16 feet high. The effectiveness of noise reduction by increasing the noise wall height also varies with the receptor's distance and elevation. The noise reduction decreases as the distance increases or the elevation decreases.

When the Sanders precast wall is extended 30 ft. east, the noise reduction is 0.2 dBA, 0.3 dBA and 0.3 dBA at R1, R2 and R3, respectively. A noise reduction of 0.5 dBA can also be achieved at R27 by extending the AAC wall 30 ft. west. In other words, making the Sanders or AAC noise walls longer may not provide noise reduction as much as expected at those houses living close to the ends of LOS walls.

After installing the noise walls, most of the receivers in the three areas are well outside the N66 noise distributions. The predicted average noise reductions are 4.4 dBA, 11.4 dBA and 8.7 dBA right after installing the noise walls in NSA1, NSA2 and NSA3, respectively. In the end of design year, only 33% of the receivers in NSA1, 56% of the receivers in NSA2 and 100% of the receivers in NSA3 can achieve a noise reduction of 5 dBA or more.

8.1.6 Pre- and Post-installation Community Noise Surveys

Both the pre- and post-installation surveys consisted mainly of the same respondents. The response rate for the owner-occupied homes was approximately 12% greater than that for the renter-occupied homes. Almost 90% of the respondents considered traffic noise as their greatest concern. About 62% of the respondents perceived a significant increase in both traffic volume and truck traffic volume during the time they had lived in

their homes. The longer the respondents had lived in the study areas, the greater traffic increase the respondents perceived. However, 87% of the respondents, particularly those could not view the traffic above the noise walls, perceived no change or a decrease in truck traffic before and after construction. The installation of noise walls produced positive perceptions about the change of traffic truck. Blocking the view of traffic provides some psychological relief to the residents.

Over 84% of the respondents had perceived a significant or moderate increase in traffic noise. The increase of traffic noise occurred gradually and slowly over time. In the pre-installation survey, 70% of the respondents rated the noise level very loud, 27% rated the noise level loud, and 2.7% rated the noise level no problem. About 39% of the respondents perceived noticeable noise on weekdays, and 10% perceived noticeable noise on weekends. No respondents perceived noticeable noise on holidays. Traffic noise level was more noticeable during daytime, particularly during the after-school time. Also, the noise impact was greater during nighttime than during daytime before installing the noise walls.

In the post-installation survey, 26% of the respondents rated the noise level every loud, 52% rated the noise level loud, and 21% rated the noise level no problem. Obviously, the respondents in the project area received a perceivable noise reduction after the installation of the noise walls. The noise walls significantly mitigated the impacts of traffic noise from I-465 on the respondents' life quality. The greater noise reduction was perceived by the respondents in NSA2 and NSA3 with conventional noise walls than those in NSA1 with LOS walls. The view of traffic above the noise wall might play an important part in respondents' perception of the post-installation noise level and impact. No effects of the respondents' age and gender were identified. The installation of noise walls have improved both safety and security for kids playing in their backyards.

In NSA2 and NSA3 with the conventional noise wall, about 53% of the respondents were pleased with appearance of the conventional noise wall. In NSA1 with the LOS walls, however, about half of the respondents were displeased with appearance of the LOS walls. For these respondents displeased with the appearance of the LOS walls, about 70% responded that the LOS walls should be either higher or longer. About 75% of the respondents felt unhappy about viewing traffic above the noise walls. The waviness occurred in the outer skin on the Noise D-Fence wall might also play an important part in the respondents' perceptions of the appearance of the LOS walls.

Over 70% of the respondents had never complained to the agency about the traffic noise in their neighborhoods. Almost 80% of the respondents were not familiar with or had limited familiarity with the federal noise regulations and INDOT noise policy. Also, about 71% of the respondents had limited familiarity or were not familiar with traffic noise abatement measures.

About 66% of the respondents indicated that noise walls should be built even if the cost effective threshold is exceeded. About 18% of the respondents would accept a cheap alternative to provide some noise reduction. Also, 82% of the respondents expressed no willingness to contribute money if the cost effective threshold is exceeded. Of those respondents willing to contribute money, the average amount of money they would like to pay is \$2160.

About 54% of the respondents indicated that alternative walls with limited noise reduction should be built even if the cost effective threshold is exceeded. When asked if it is worth the money to build these noise walls, about 67% of the respondents in NSA2 or NSA3 with conventional noise walls answered yes and 50% of the respondents answered no in NSA1 with LOS walls.

When asked how the respondents would prefer to receive information on public involvement in traffic noise, about 56% of the respondents would prefer to receive the information by mail, 22% by email, 13% by TV, and 9% by newspaper. No respondent would prefer to receive the information by any type of social media, such as Facebook and Twitter, regardless of respondent's age and gender.

8.2 Recommendations

Based on the findings above, the following recommendations are made:

- To deal with increasing public noise concerns, it is advisable for INDOT to opt to participate in a Type II program or develop a retrofit noise wall program such as a LOS wall policy. However, this type of program or policy should be subject to the funds available.
- It should establish a maximum noise wall height in the INDOT traffic noise policy. Based on this study, a maximum noise wall height of 22 ft. is recommended to ensure the acoustic feasibility and constructability.
- Due to the problem of increasingly rising prices, the cost-effectiveness of noise abatement in the current INDOT traffic noise policy should be increased to \$35,000 per benefited receiver.
- It is recommended that INDOT should consider use of the third party funding for noise abatement within the State right-of-way, particularly for state retrofit projects or LOS walls.
- It is not necessary for INDOT to implement a tiered approach to cost reasonableness statewide, considering that the regional cost differences of construction of noise walls are not evident within the State.
- So far, there is no sufficient, reliable data to arrive at the maximum square footage per benefited receptor for INDOT to measure the cost-effectiveness of a noise abatement measure. INDOT Environmental Services should be contacted for further investigation.
- When determining the cost-effectiveness for precast concrete and CMU block noise walls, an estimated cost of \$34 per square foot of barrier is recommended for INDOT. Also, a discount rate of 4% can better reflect the true inflation in the construction costs of noise walls.

- It is advisable for the INDOT traffic policy to define the feasibility of noise abatement in terms of the first row receptors rather than all impacted receptors.
- It is not feasible to abate traffic noise through lowering speed limits.
- To avoid possible negative perceptions, a noise wall with reflective surface should not be utilized.
- For LOS walls, the minimum height should be at least 6 ft., but tall enough to block the view of trucks.
- Since this study revealed that the appearance of LOS wall did affect the public perception of its actual performance, public involvement should be further encouraged to improve the appearance of LOS walls subject to no additional costs incurred.
- INDOT should further step up educational outreach for traffic noise abatement.

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APPENDIX A. PRE-CONSTRUCTION COMMUNITY SURVEY QUESTIONNAIRE

1. Questions about yourself.

(a) Age _____ (b) Sex _____

2. How many years have you lived in the present neighborhood? _____

3. Do you own or rent your home?

(a) Own (b) Rent (c) Other (specify) _____

4. Which of the following best describes your home?

(a) Single family (b) Duplex house (c) Condominium (d) Apartment

5. Please indicate the number of persons and their age brackets living in your house, including yourself.

Age (years)	<6	6-18	19-22	22-30	31-40	41-50	51-60	61-70	>70
No. of persons									

6. As a nearby resident, what do you like least about traffic on I-465?

(a) Traffic volume (b) Congestion (c) Noise (d) Emissions (e) Danger from vehicles

7. Which of the following best describes the change in traffic volume on I-465 during the time you have lived in your home?

(a) Significant increase (b) Moderate increase (c) About the same (d) Decrease

8. Which of the following best describes the change in truck traffic on I-465 during the time you have lived in your home?

(a) Significant increase (b) Moderate increase (c) About the same (d) Decrease

9. Which of the following best describes the change in traffic noise level from I-465 during the time you have lived in your home?

(a) Significant increase (b) Moderate increase (c) About the same (d) Decrease

10. As a resident, how would you rate the level of the current traffic noise level from I-465?

(a) Very loud (b) Loud (c) No problem

11. As a resident, how would you rate the effect of the current traffic noise from I-465 on your quality of life?

(a) Very negative (b) Negative (c) No effect

12. Which of the following best describes the impact of traffic noise from I-465 on your outside activities?

	All the time	Several times per week	Several times per day	Occasionally	Not at all
Ability to keep window open					
Talk to others					
Listen to TV					
Talk on the phone					
Sleep					
Outdoor activities					

13. How would you rate the impact of traffic noise from I-465 during the daytime?

(a) Very disturbing (b) Disturbing (c) Only slightly disturbing (d) Not disturbing

14. How would you rate the impact of traffic sounds from I-465 during the nighttime?

(a) Very disturbing (b) Disturbing (c) Only slightly disturbing (d) Not disturbing

15. On which of the following days is the traffic noise from I-465 most noticeable?
- (a) Saturday (b) Sunday (c) Weekdays (d) Holidays (e) All of the above
16. During which of the following time periods is the traffic noise from I-465 most noticeable?
- (a) 6am-9am (b) 9am-12pm (c) 12pm-3pm (d) 3pm-6pm (e) 6pm-10pm (f) 10pm-6am
17. How often do you and your family members play or relax in your yard in warm weather?
- (a) Everyday (b) Several times a week (c) Once a week (d) Occasionally (e) Not at all
18. Federal regulation, 23 CFR Part 772-Procedures for Abatement of Highway Traffic Noise and Construction Noise, provides guidance for highway noise reduction measures and requirements for considering noise reduction measures. Which of the following best describes your level of familiarity with this regulation?
- (a) Not at all (b) Limited (c) Fair (d) Very familiar
19. INDOT's Traffic Noise Policy provides specific procedures and standards for highway traffic noise reduction. Which of the following best describes your level of familiarity with this policy?
- (a) Not at all (b) Limited (c) Fair (d) Very familiar
20. Which of the following best describes your level of familiarity with traffic noise reduction measures?
- (a) Not at all (b) Limited (c) Fair (d) Very familiar
21. Have you ever complained to government agencies about the noise in your neighborhood?
- (a) Never (b) Yes, once (c) Yes, two to three times (d) Yes, many times
22. Traffic noise reduction measures, such as traffic noise walls, are eligible for federal taxpayer funding if a 5 decibel reduction can be achieved at a cost not exceeding \$25,000 per household. Noise walls cost approximately \$ 2 million per linear-mile. Which of the following describes your expectation for building noise walls?
- (a) Noise walls should not be installed using taxpayers' money if the \$25,000 per household threshold is exceeded.
- (b) Noise walls should be installed using taxpayers' money even if the \$25,000 per household threshold is exceeded.
- (c) Other cheaper alternatives rather than noise walls should be installed to provide some noise reduction using taxpayers' money if the \$25,000 per household threshold is exceeded.
23. If the \$25,000 per household threshold is exceeded and federal taxpayer funds cannot be justified, yet you are in favor of installing traffic noise barriers, would you be willing to contribute money individually or through an association to pay for the construction costs?
- (a) Yes (b) No
24. If you answered "Yes" to Question 23, how much money would you be willing to contribute to pay for the construction costs?
- (a) Less than \$1,000 (b) \$1,000-\$3,000 (c) \$3,000-\$5,000 (d) Other (specify)
25. Alternatives to noise walls are typically smaller and may cost less than noise walls and have been used to block the line of sight between a commercial or residential area and a roadway or structure. However, these alternative walls may provide only limited noise reduction. Which of the following best describes your preference for using these alternatives to noise walls?
- (a) These alternative walls should be not installed using taxpayers' money if the \$25,000 per household threshold is exceeded.
- (b) These alternative walls should be installed using taxpayers' money if the \$25,000 per household threshold is exceeded.
26. How would you prefer to receive information on public involvement in decision-making for highway traffic noise issues?
- (a) Mail (b) Email (c) TV (d) Newspaper (e) Radio (f) Facebook/Twitter (g) Other (specify)

APPENDIX B. POST-CONSTRUCTION COMMUNITY SURVEY QUESTIONNAIRE

1. Questions about yourself.

(a) Age _____ (b) Sex _____

2. How many years have you lived in the present neighborhood? _____

3. Do you own or rent your home?

(a) Own (b) Rent (c) Other (specify) _____

4. Which of the following best describes your home?

(a) Single family (b) Duplex house (c) Condominium (d) Apartment

5. Please indicate the number of persons and their age brackets living in your house, including yourself.

Age (years)	<6	6-18	19-22	22-30	31-40	41-50	51-60	61-70	>70
No. of persons									

6. Which of the following best describes the change in truck traffic on I-465 before and after the construction of the sound walls?

(a) Significant increase (b) Moderate increase (c) About the same (d) Moderate decrease (d) Significant decrease

7. Which of the following best describes the change in traffic noise level from I-465 since the completion of the construction of the sound walls?

(a) Significant increase (b) Moderate increase (c) About the same (d) Moderate decrease (d) Significant decrease

8. As a resident, how would you rate the level of the current traffic noise level from I-465 since the completion of the construction of the sound walls?

(a) Very loud (b) Loud (c) No problem

9. As a resident, how would you rate the effect of the current traffic noise from I-465 on your quality of life?

(a) Very negative (b) Negative (c) No effect

10. Which of the following best describes the impact of traffic noise from I-465 on your outside activities since the construction of the sound walls?

	All the time	Several times per week	Several times per day	Occasionally	Not at all
Ability to keep window open					
Talk to others					
Listen to TV					
Talk on the phone					
Sleep					
Outdoor activities					

11. How would you rate the impact of the traffic noise from I-465 during the daytime since the construction of the sound walls?

(a) Very disturbing (b) Disturbing (c) Only slightly disturbing (d) Not disturbing

12. How would you rate the impact of traffic sounds from I-465 during the nighttime since the construction of the sound walls?

(a) Very disturbing (b) Disturbing (c) Only slightly disturbing (d) Not disturbing

13. How often do you and your family members play or relax in your yard in warm weather since the construction of the sound walls?
- (a) Every day (b) Several times a week (c) Once a week (d) Occasionally (e) Not at all
14. How pleased would you say you are with the appearance of the sound walls?
- (a) Very pleased (b) Somewhat pleased (c) Neutral (d) Somewhat displeased
15. Are you able to view the traffic above the sound walls?
- (a) Yes (b) No
16. If you answered "Yes" to the previous question, how do you feel about being able to see traffic above the sound walls?
- (a) Very unhappy (b) Unhappy (c) Neutral
17. How much do you feel the sound walls have changed the noise levels in your neighborhood?
- (a) Significant decrease (b) Minor decrease (c) No change (d) Minor increase
18. Do you feel that the sound walls are worth the money that it cost to build them?
- (a) Yes (b) No
19. Additional comments on the sound walls constructed.

About the Joint Transportation Research Program (JTRP)

On March 11, 1937, the Indiana Legislature passed an act which authorized the Indiana State Highway Commission to cooperate with and assist Purdue University in developing the best methods of improving and maintaining the highways of the state and the respective counties thereof. That collaborative effort was called the Joint Highway Research Project (JHRP). In 1997 the collaborative venture was renamed as the Joint Transportation Research Program (JTRP) to reflect the state and national efforts to integrate the management and operation of various transportation modes.

The first studies of JHRP were concerned with Test Road No. 1—evaluation of the weathering characteristics of stabilized materials. After World War II, the JHRP program grew substantially and was regularly producing technical reports. Over 1,500 technical reports are now available, published as part of the JHRP and subsequently JTRP collaborative venture between Purdue University and what is now the Indiana Department of Transportation.

Free online access to all reports is provided through a unique collaboration between JTRP and Purdue Libraries. These are available at: <http://docs.lib.purdue.edu/jtrp>

Further information about JTRP and its current research program is available at: <http://www.purdue.edu/jtrp>

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